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A Study on the Probability of Failure Model Based on the Safety Factor for Risk Assessment in a Water Supply Network

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Abstract

Water pipes corrode as the endurance period elapses, or become deteriorated according to the buried environment, sometimes causing functional failure and problems with stable water supply. Stable and continuous water supply for consumers requires the risk assessment of water pipes. The safety factor has been used in many fields as a direct evaluation index that can express the state of a facility and is also used as a reference to judge the necessity of pipe renewal. In this study, the safety factor was calculated in order to establish the Probability of Failure model, by using result data such as the pipe property and ratio of residual stress from the technological inspection of waterworks.

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1. Introduction

1.1 Background and Objectives of This Study

Most of the water pipes in Korea have been laid during a period of rapid economic growth in the 1970s and 1980s. It was felt necessary to deploy a system that prepares for the requirement of water, and supplies water reliably, without water outages. With the passage of time, water pipes can become rusted or slowly deteriorate because of the surrounding environment such as soils, roads, and ground depth, resulting in the outage of water and improper functioning. As of 2013, 1.381 pipes were more than 20 years old, and required improvement in 10 years;

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this is 27.17% of the total number of pipes. In 2024, that is 10 years later, 2,666 pipes will require improvement, which is 52.45% of the total number of pipes. Based on this data, it is expected that the risk of a water supply outage has significantly increased. In addition, deterioration is expected at the same time, since all the water pipes were laid during a short period of rapid economic growth. Thus, it is also expected that tremendous expense will be required in order to carry out these improvements, and it is inevitable that a more effective plan has to be prepared for improvement, while utilizing limited resources [1].

In order to supply water to users reliably and continuously, it is necessary to evaluate the risk of water outage, and prepare solutions for reducing the risk of water outage, by utilizing the results of a risk assessment of water supply systems. It is also necessary to accord high priority to the improvement of pipes in order to maintain water supply systems properly. For evaluation of the risk of water outage, the estimation of the pipe failure rate should be done by analyzing the various causes related to damage of the pipes. Therefore, this study intends to propose a method for estimation of the pipe failure rate, utilizing the safety coefficient calculated based on various factors that influence the failure of pipes.

1.2 Research Details

In this study, the target area was selected first. In order to understand the situation in that area, data such as the diameter of pipes in the area, the year when they were laid, type of pipe used, and event history were collected from the recovery records of water leakage, event log records, and the existing water supply situation of users. The pipe failure rate was estimated with the exponential model, using the optimized correlation coefficient by applying the actual accident log data, which was based on the safety coefficient of the pipeline. The correlation coefficient for the model was derived using the least squares technique.

2. Research from Previous Studies and Theoretical Investigation

2.1. Risk Analysis

A water supply system should have the capability to supply a certain amount of water continuously, even in abnormal conditions such as water leakage and the failure of pipes. If the water supply is cut off, resulting in difficulty for the users because of the non-availability of water, then it would be a negative accident. In terms of uncertainty classification, it is said to be a risk, and not an opportunity. In this case, the stochastic figure that includes uncertainty factors such as leakage and failure of pipelines, damage level caused by the cutting off of water, and the margin for mitigation of damage can be considered. The water outage risk presented in this study is an index that includes the probability that the supplier cannot provide water for users, results of damage (time for repair of broken pipes, water demand), and redundancy.

2.2. Estimated Model for Pipe failure Rate

2.2.1. Research trends

The estimation of the pipe failure rate falls into two categories: a physical model and statistical model. The physical model is based on a deterioration mechanism that directly influences the failure of pipes, and is made by understanding the extent of damage of the pipes, such as scale and rust. Thus, the physical reasons for pipe failure are clear and a wide range of variables and data can be used. However, it is very difficult to measure or examine all the pipes for the factors that cause failure, because it takes a lot of time, and is expensive. The statistical model applies two methods: one is by estimating an exponential function or linear function that has a large correlation, and the other is by using established models such as the regression analysis model, Markov model, Poisson model, or Cohort survival model. The statistical model is a macroscopic method that uses the data stored over a long period, and allows data collection with relatively low expenses. However, it has the disadvantage of not providing physical evidence of the factors that caused the deterioration of the pipes. The statistical model quantifies the structural deterioration of the pipes by historical data, and goes through a process that analyses the frequency of accidents, sequence of accidents, and status of the pipes from event logs of the water supply system.
In this study, the pipe failure rate was calculated using the statistical model based on the data collected. The earlier studies that used the exponential model in calculating the pipe failure rate are Shamir & Howard (1979), Walski & Pelliccia (1982) and Park & Loganathan (2002). Shamir & Howard (1979) developed the regression equation for an annual failure event \( N(t) \) using pipe failure data for various features of pipes which are similar. When analyzing data, the factors show symptoms of failure on pipes classified and grouped properly. Through this approach, the credibility of the statistical analysis results could be increased. From the results, it was inferred that the factor that had the highest influence on the failure of pipes was the age of the pipe. Hence, a model was developed in which the failure rate increases exponentially. Walski & Pelliccia (1982) proposed, based on experiments, an intensified exponential model by adding two factors: the failure history of pipes made by the old method, and the diameter of the pipe. The first additional factor considers the high probability of pipe failure in the case of old pipes that have had failure earlier; the second factor considers the higher possibility of failure with a larger diameter of pipe [2,3,4].

This study intended to propose a model equation, based on the exponential model, in which the pipe failure rate increases exponentially as the safety coefficient of the pipe decreases. The safety coefficient is calculated considering the various factors that affect pipe failure, such as the type of pipe, age of the pipe (existing thickness, internal corrosion depth, and external corrosion depth), internal pressure (water, and water-hammer), and external load (soil pressure, load of cars, load due to ice layer, and soil expansion).

### 2.2.1. Safety factor

The safety factor is represented by a ratio indicating the proportion between the load applied to the pipe and the allowed load, or between the applied stress and existing strength. It is an index to represent the ability of the water pipe to resist the load (or stress); the safety coefficient increases when the existing strength is higher, and the safety coefficient decreases as the applied stress increases.

The safety coefficient in the water supply system is largely used for direct relative assessment of the pipes that are already laid. This study intended to actually measure the safety coefficient that is calculated through residual stress in the pipe by utilizing data that are obtained either directly or indirectly through the previous studies. Based on the results, it is intended to present an evaluation index that is able to perform relative indirect assessment of the pipes that are already laid.

The procedure to calculate the safety coefficient is shown below.

- **Step 1** – Understand the environment in which the pipes have been laid, through investigation of field data.
- **Step 2** – Estimate the existing thickness of the pipes based on basic information such as type of pipe, age of pipe, thickness of pipe, diameter of pipe, water pressure, water-hammer pressure, type of soil, soil unit mass, depth of laid in, laid in environment, and pipe support angle.
- **Step 3** – Calculate the existing strength.
- **Step 4** – Investigate the internal pressure, and the influence of factors for the external load, and for the internal and external corrosion of the pipe.
- **Step 5** – Calculate the internal pressure and external load.
- **Step 6** – Finally, calculate the stress applied to the pipe.
- **Step 7** – Estimate the safety coefficient by comparing the stress due to internal pressure with the stress due to external load, and setting the larger value as applied stress.

- **Residual stress**

  With the passage of time, there will always be rust or corrosion, caused by various physical or chemical actions. As this process continues, the pipe loses its ability to resist the applied load and eventually results in failure. Thus, the depth of corrosion should be known in order to estimate the existing strength. The depth of corrosion can be calculated using data such as the age of the pipe and type of pipe. However when the pipe is in use, a test piece of the pipe cannot be obtained, and hence, its physical strength cannot be tested. In such a case, the residual strength can be estimated from the corrosion rate, by using either an ultrasound test or by the measurement of external corrosion, and then applying the estimation model equation shown in Table 1.
Table 1. Theoretical background for the Probability of Failure prediction model using the safety factor

| Safety Factor | SF = \( \frac{\sigma_{\text{residual stress}}}{\sigma_{\text{applied stress}}} \) | Where, SF = safety factor, \( \sigma_{\text{residual stress}} = \text{residual strength(kgf/cm}^2) \), \( \sigma_{\text{applied stress}} = \text{applied stress(kgf/cm}^2) \)
|---------------|---------------------------------|---------------------------------|
| \( \sigma_{\text{residual stress}} \) | DCIP | External corrosion(\( p_{\text{ec}} \)) | a : 0 | b : 1.736 | c : 1.737 |
| | | Internal corrosion(\( p_{\text{ic}} \)) | = aT + b(1-e^{-cT}) | a : 0.022 | b : 1.582 | c : 0.810 |
| | | External corrosion(\( p_{\text{cc}} \)) | a : 0.030 | b : 1.406 | c : 0.863 |
| | | Internal corrosion(\( p_{\text{tc}} \)) | a : 0.079 | b : 2.830 | c : 2.135 |
| \( \sigma_{\text{applied stress}} \) | DCIP | Residual stress | = a\( p_c \) + b | a : -4573.2 | b : 4520.3 |
| | SP | Residual stress | a : -3776.8 | b : 4132.1 |

\( \sigma_n \) = circumferential stress by internal pressure(kgf/cm²), \( t \) = pipe thickness(mm), \( d \) = inside diameter of the pipe(mm), \( P_{\text{total}} \) = total internal pressure(kgf/cm²)

Where, \( \sigma_n = \text{circumferential stress by internal pressure(kgf/cm}^2 \), \( t = \text{pipe thickness(mm)}, \( d = \text{inside diameter of the pipe(mm)}, \( P_{\text{total}} = \text{total internal pressure(kgf/cm}^2 \))

Where, \( W_e = \text{vertical load(kg/cm)}, \gamma = \text{unit soil weight(kgf/cm}^3 \), \( H = \text{soil depth(cm)} \)

Where, \( W_e = \text{external pressure by truck load(kgf/cm}^2 \), \( P_{\text{rw}} = \text{rear wheel load of truck(kg)}, \( n = \text{number of trucks aligned along the occupied width}, \( L = \text{interval from the center of the rear wheel(cm)}, \( b = \text{rear wheel folding width(cm)}, \( C = \text{interval among the rear wheel centers of neighboring trucks(cm)}, \theta = \text{dispersion angle(°)}, a = \text{wheel tread field(cm)}, i = \text{impact factor} \)

\[ I = \begin{cases} \text{Soil depth(m)} & \text{Impact factor} \\ H \leq 1.5 & 0.5 \\ 1.5 < H \leq 6.5 & 0.65 - 0.1H \\ H > 6.5 & 0 \end{cases} \]

Where, \( \sigma_{\theta,s} = \text{bending stress by external load in the lower pipe(kgf/cm}^2 \), \( f = \text{form coefficient}, Z = \text{sectional coefficient of the unit width}, Z = t^2/6(\text{cm}^2), t = \text{pipe thickness(cm)}, W_e = \text{earth pressure(kgf/cm}^2 \), W_t = \text{traffic load(kgf/cm}^2 \), R = \text{average radius of the pipe(D}_m/2 = d/2), E = \text{elasticity coefficient of the pipe(Young Modulus)(kgf/cm}^3 \), I = \text{sectional secondary moment per unit width}, I = t'/12(\text{cm}^3), E' = \text{subgrade reaction coefficient(Reaction Modulus)(kgf/cm}^3 \), K_u, K_b, K_x = \text{bending moment coefficient at the pipe by supporting angles} \)

Where, \( \sigma_{\theta,d} = \text{bending stresses(kgf/cm}^2 \), \( t = \text{pipe thickness(cm)}, M_e = \text{bending momentum by earth pressure(kgf/cm}^2 \), \( M_t = \text{bending momentum by traffic load(kgf/cm}^2 \), Z = \text{sectional coefficient of the unit width}, Z = t^2/6(\text{cm}^2), t = \text{pipe thickness(cm)} \)

\[ \sigma_{\theta,s} = \frac{2}{IZ} (W_e + W_t) \times K_b R^2 E I + (0.06146 K_e - 0.08303 K_b) E' R^5 \]
Applied stress
The applied stress is caused by internal pressure and the external load. The internal pressure includes the water pressure applied during usage, and the water-hammer pressure when a water-hammer effect is seen. External load includes soil pressure, car load, icing load, and soil expansion.

- Stress due to internal pressure
  In water pipes, stress is generated circumferentially by internal pressure. In this case, the pipe should have a minimum thickness in order to resist the circumferential tensile stress. The circumferential stress is estimated from the operating pressure and water-hammer pressure.
- Stress due to external load
  Soil pressure (soil load) is generally the load applied on top of the pipe, and is the same as the weight of the soil. This formula is estimated without any consideration for soil friction, and considering that only the soil weight is directly applied on the pipe, disregarding the side friction. Actually, the weight of the soil column on the pipe is not fully transferred to the pipe. The load is offset by the shear friction force between the columns of soil located close to the contact surface of the pipe. Due to the ductility of the material of the pipe, the pipe tends to bend against the soil pressure.
  A car load is an active load; it refers to a load applied by the movement of a car, truck, train, or other moving vehicle on the pipe that is not laid deeply. This load is affected by the weight of cars, tire pressure, speed of cars, roughness of the surface, type of pavement, and distance from the load to the pipe.
  In the calculation of load strength applied to pipe, the dispersion angle method is used. It considers dispersion of the vertical earth width to 20~45cm and the occupancy width of the car to 175cm in the horizontal direction. The impact factor is used to consider the load depending on the depth at which the pipe is laid.

Estimation of stress depending on the type of pipe
- Steel pipe
  For a steel pipe, the formula of stress due to internal pressure is applied. The effects of car weight and soil pressure are considered in the case of external load estimation. Considering the strain rate caused by such loads and the bending stress on the bottom of the pipe, the thickness of the pipe is determined.
- Cast-iron pipe (including DIP, CML_DIP)
  A bending stress by external load is presented in Table 1.

3. Research Method

3.1. Research Area and Characteristics

The target area for this study is a YC industrial waterworks that supplies water to the national industrial complex in Y city and the ironworks, and also supplies water regularly for living to Y city, G city, S city, K gun, and B gun.
There are two intake stations of the water source; their capacity is 540,000 m$^3$/day each, and the total water requirement of this area is 16,862 m$^3$/day. The water pipeline facilities are divided into 5 systems (Y system, E system, O system, N system, and B system), and the total length is 119.3 km. The Y system extension is 54.6 km, which is 46% of the total; the B system extension is 27.5 km, or 23%; the E system extension is 15.9 km, or 13%; the N system extension is 13.6 km, or 11%; and the O system extension is 7.7 km, or 7%. Each system was divided and organized by diameters of pipe, type of pipe, year of laying, number of joints and tied together with structurally same or tied with same water supply path; and also divided by sectors. In this study, the pipelines are named as follows. The first initial (S1, S2, S3) represents the source of the water. The digit S1 denotes water from D intake facility, S2 from E facility, and S3 from D&E facility. The second initial (Y, N, O, E, B) represents the target area, and is classified by diameter, type of pipe, year of laying, and joint details. For instance, pipe S1Y1 means, “No. 1 pipe from Y system using water from D intake facility”. The schematic diagram of each system in the target area is shown in Fig. 2; the amount of water in the schematic diagram is shown in Table 2, and the general specifications of the pipe are shown in Table 3.

| Table 2. Inflow & Outflow Quantity of Target Area |
|---|---|---|---|---|
| Code | Quantity(m$^3$) | Direction | Code | Quantity(m$^3$) | Direction |
| Q_D | 374,072 | inflow | Q_Y1 | 33,760 | outflow |
| Q_E | 448,119 | inflow | Q_Y2 | 74,000 | outflow |
| Q_{S,B,K} | 33,777 | outflow | Q_Y3 | 192,000 | outflow |
| Q_O | 283,000 | outflow | Q_Y4 | 205,654 | outflow |

| Table 3. Pipe Data of Target Area |
|---|---|---|---|---|---|
| Pipe ID | Type | Diameter(mm) | Age(year) | Length(m) | Service Area |
| S1Y1 | SP | 1,650 | 36 | 7,804 | Y, G |
| S1Y2 | SP | 1,650 | 36 | 5,425 | Y, G |
| S1Y3 | SP | 1,650 | 36 | 4,780 | Y |
| S1Y4 | SP | 1,650 | 36 | 8,084 | Y |
| S1Y5 | SP | 1,650 | 36 | 9,225 | Y |
| S1Y6 | SP | 1,650 | 36 | 5,999 | Y |
| S1Y7 | SP | 1,500 | 36 | 4,861 | Y |
| S1Y8 | SP | 1,500 | 36 | 1,014 | Y |
| S1Y9 | SP | 1,200 | 36 | 81 | Y |
| S1Y10 | SP | 1,000 | 36 | 5,813 | Y |
| S1Y11 | DCIP | 900 | 36 | 1,501 | Y |
| S1O1 | SP | 900 | 29 | 7,744 | G |
| S1N1 | SP | 900 | 24 | 5,501 | Y, G |
| S1N2 | SP | 1,650 | 24 | 523 | G |
| S1N3 | SP | 1,500 | 24 | 4,995 | G |
| S1N4 | SP | 1,350 | 24 | 2,601 | G |
| S1E1 | SP | 2,200 | 22 | 6,553 | Y, S, B, K |
| S1E2 | SP | 2,000 | 22 | 9,340 | Y |
| S1B1 | SP | 1,500 | 14 | 14,823 | Y |
| S1B2 | SP | 1,350 | 14 | 1,747 | Y |
| S1B3 | SP | 1,200 | 14 | 4,415 | Y |
| S1B4 | SP | 1,000 | 14 | 6,522 | Y |
3.2. Estimation Method for Pipe failure Rate

3.2.1. Estimation method for safety coefficient

Failure of a pipe occurs due to various factors such as type of pipe, age of pipe, environment in which it is laid, depth of pipe, operating conditions, and soil conditions. However, it is not easy to get such data and to quantify the information, and it is practically impossible to consider all the factors in the estimation of the pipe failure rate.

In this study, a concept called the safety coefficient is introduced in order to present quantitatively many factors that influence the failure of pipes with limited sources. The safety coefficient is an index that represents the ability of a pipe to resist stresses applied to the pipe, and is the ratio of applied stress to residual limit stress. The safety coefficient is widely used as a direct evaluation index to represent the status of pipe failure in present facilities.

With the passage of time, rust or corrosion occurs in pipes due to various physical and chemical actions. After repeating this process many times, the pipe eventually loses its ability to resist the applied load. Residual strength refers to the stress retained at this time. Corrosion depth is estimated from the age of the pipe; Existing strength is estimated after estimation of the corrosion rate in Table 1, which depends on the existing pipe thickness rate and corrosion depth for both internal and external loads. Several models such as the linear model, involution model, and exponential model are available in order to estimate the corrosion depth. Lee et al. (2004) have reported that pipes show a tendency for fast corrosion in the beginning, and then turn to slow corrosion. It appears that, as the number of years after the year of laying becomes longer, the external corrosion product increases as well, and in turn, those products limit the reaction between pure metal and the factors that cause corrosion; eventually it has an impact on the speed of the electrochemical corrosion mechanism [7]. With this consideration, in this study, we selected the exponential model, which has a similar tendency in corrosion by referring to the previous studies.

The stresses are applied to a pipe due to internal pressure and by external load. Internal pressure includes water pressure applied during usage, and water-hammer pressure, which appears when there is a water-hammer effect. External load includes soil pressure, car weight, icing load, and soil expansion. Since the water pipes are largely
made of steel or iron, soil pressure and car weight are considered as external loads based on the water supply criteria standard 2010. A stress because of internal pressure is caused by water pressure or water hammer pressure. In the external load, the most widely used formula is the Marston’s formula used for soil pressure. It is a formula used for calculation when the load that the pipe receives from a vertical soil column is offset by the shear friction force between the columns of soil located closely to the contact surface. The horizontal soil pressure is calculated using the Rankine’s formula. The Marston’s formula is mainly applied when the pipe is hard; since our target pipeline uses mainly steel and iron, which are ductile, the Marston’s formula is applied.

The Criteria standard for water supply system(2010) suggests the use of the weight of the rear wheels of the vehicle, and to disregard the weight of the front wheels. Therefore, in this study, the above criteria are applied for estimation of the effect of car weight. Since there is no data or insufficient data for the effect of the environment where the pipe is laid, the support angle of the pipe, etc., some constants required in the calculation are replaced by numbers recommended in the previous studies. In the case of the environment where the pipe is laid, some rough information on the area(road or not) where the pipes were laid is available, but there is no information as to which values were applied as factors.

Thus, in case of use as a road, it is estimated with DB-24(rear wheel weight of 9,600kg), and in the area of mountains, where there is no pavement where cars can be allowed, car weight is not applied. The support angles of the pipe used are those widely used, as suggested in the criteria standard for water supply system(2010)(90° for SP and 60° for DCIP). With the estimated soil pressure and car weight mentioned above, the external stress is estimated through the external load stress estimation formula. The applied stress, which is the root cause of failure, was studied on pipes with a larger diameter because it has more influence on the failure. In this study, the safety coefficient was estimated by using the larger diameter.

3.2.2. Grouping method for safety coefficient section

It is necessary to calculate the safety coefficient for the pipes that have had accidents before, and find the correlation between the safety coefficient and the failure rate. It is intended to propose a model that predicts the pipe failure rate in this case with the safety coefficient as the input value. The number of accidents in the area was 49, which includes all the accidents in the location. Considering the average period of 30 years for the age of the pipe in the area, it is felt that there might be many errors in the available data. Therefore, as an alternative, it was decided to identify the safety coefficient for each sector and perform the grouping by analyzing the data within the sector or the group. With this approach, the credibility of the results of the statistics can be improved, and the tendency of failure depending on the safety coefficient. In this study, due to the lack of data as mentioned above, the safety coefficient was divided into 8 groups from 0.2 to 0.9, and the tendency of the failure rate was determined based on the safety rate.

3.2.3. Estimation of the pipe failure rate model

The tendency in the area shows that the failure rate decreases as the safety coefficient increases and the failure rate model is deployed by the exponential function as shown below.

\[ y = ae^{-bx} \]  \hspace{1cm} (1)

where, \( y \): failure rate per unit length (number/km/yr), \( x \): Safety Factor

In the target area, the year of the oldest pipe was identified as criteria, and classification was done based on the years after which the accident took place after the pipe was laid. The safety coefficient is obtained based on the data for the pipe with accidents. After estimation of the safety coefficient, the accident event log is applied to the model formula. The safety coefficient of the area appears differently and by grouping these values per distance and is applied to the corresponding failure rate. In order to calculate the value of constants for the failure rate model, the values of \( a \) and \( b \) were arrived at using the sum of squares of the difference between the accident log data and predicted data of the model, to the minimum deriving the optimum correlation coefficient and deploying the failure rate model formula through the correlation coefficient.
4. Results of the Study and Investigation

4.1. Results of estimation of the Pipe Failure Rate

4.1.1. Results of estimation of the safety coefficient

From the results of the estimation of the safety coefficient with respect to the pipeline in the target area, it was inferred that when the safety coefficient is less, accidents happen more frequently. The higher the safety factor, the less is the occurrence of accidents. Especially, the safety coefficient varies from a minimum of 1.2 to a maximum of 7.6. When the safety coefficient dispersion graph shows a value less than 2.5, it means that the pipes that require either replacement or improvement are 43% of the total; and when it is 1.5, the corresponding value is 18%. It is clear that the pipes which require improvement will be more with the passage of time, since the range 2.5–3.5 covers 25% of the total cases.

4.1.2. Results of grouping of safety coefficient based on sectors

In the results of the estimation of the safety coefficient, the lowest value observed was 1.2. By grouping this in the range from 0.2 gap to 0.9 gap, and representing the results of the failure rate with the corresponding safety coefficient, it is seen that the graph moves to the exponential function after a 0.7 gap. Similar results are seen for the 0.8 and 0.9 gaps as well. It was clear that there is a correlation between the safety coefficient and failure rate; the failure rate decreases as the safety coefficient increases. And the failure rate increases as the safety coefficient decreases.

4.1.3. Results of selection of Pipe failure rate model

As the safety coefficient increases, the failure rate decreases, and it is found to be in the exponential form. Based on this information, the failure rate model was deployed using the exponential function. When the safety coefficients were grouped with the gap of 0.7–0.9, the results showed a clear trend for the failure rate. Thus, only three cases were considered. In order to calculate the value of the constants for the failure rate model, the values of a and b were arrived at using the sum of squares of the difference between the accident log data and predicted data of the model. The results of applying the exponential model are shown in Table 4.

![Fig. 3. PoF by Safety Factor at Interval 0.7(left), 0.8(middle), 0.9(right)](image)

| Category        | PoF exponential model | Equation            |
|-----------------|-----------------------|---------------------|
| SF Interval     | 0.7                   | $Y = ae^{-bx}$      |
| Coefficient     | a = 0.0471, b = 0.2696| 0.8                 |
| R               | 0.7589                | $Y = ae^{-bx}$      |
| RMSE(N/km/yr)   | 0.0069                | 0.9                 |
| Coefficient     | a = 0.0444, b = 0.2450| 0.2320              |
| R               | 0.7833                | 0.7428              |
| RMSE(N/km/yr)   | 0.0062                | 0.0066              |
From the results of the calculations for the correlation coefficient (R) and the root mean square error (RMSE) for each exponential model for different safety coefficient gaps, it was observed that the correlation coefficient has the highest value of 0.7833 corresponding to a 0.8 gap, and the RMSE had the lowest value of 0.0062. In the failure rate model, the failure rate sometimes appears to be 0. For instance, looking at the results for grouping by the 0.7 gap, it shows the failure rate as 0 corresponding to the safety coefficient value of 5. It can be noted that in this sector the distance of pipe is as long as 4.0,1 and the actual failure is low. As a result of deployment of the failure rate model, the coefficient of the exponential formula gave values of a=0.0444, b=0.2450, and the correlation coefficient 0.7833, which implies that they are related to each other. In addition, the RMSE, which is the index representing the average error between the estimated value and measured value, is very small; the two values are similar, appeared R=0.7833 which is smallest one in the selected models. Thus, the failure rate model formula that gives the number of accidents per unit length during the year was applied with the safety coefficient gap of 0.8. In the failure rate model formula, the number of accidents starts increasing when the safety coefficient drops under 2.5, and increases rapidly at the point when the safety coefficient drops under 1. According to a manual for old pipe improvement methods (2014), the recommendation is to replace the pipes when the safety coefficient is less than 1, and to decide whether to replace or repair when the value is less than 2.5. Based on this information, it can be considered that the findings of the failure rate model in this study are valid.

5. Conclusion

In this study, the failure rate was estimated by introducing the concept of a safety coefficient that considers the various environmental and operational conditions in which the pipes were laid, and the risk was estimated considering the recovery time for broken pipes, the amount of water requirement, margins, etc. Especially, in developing the failure rate model, due to the limited data, in order to acquire the representative data for the safety, data were identified by rank based on the safety coefficient. The results of the analysis showed that the case with a safety coefficient of a 0.8 gap showed a correlation coefficient value of 0.7833, and it was able to present the failure rate model with statistical analysis.

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