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Discussion on Evaluation Method for Defect Probability based on Maintenance History Data of Spillway Gate Components

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ABSTRACT:
As for the spillway gate, the maintenance work is assessed and implemented based on the qualitative data obtained from the periodical visual inspection mainly. However, it is difficult in some cases to clarify the deteriorating condition of spillway gate components only by the visual inspection.
In addition to the above qualitative data, an appropriate quantitative evaluation method is, therefore, needed to judge maintenance activities for the spillway gate.
This paper presents the results of analysis on the relation between the defect frequency of the spillway gate and the past records of its maintenance work from a statistical point of view.
The deliberation steps in this study are as follows:
- Check and review of the maintenance history data: analysis of the past maintenance records,
- Goodness of fit test: comparison between the theoretical and non-theoretical probability models, and
- Censor data effect: verification on the censor data effect to the defect probability.

The proposed method, based on the maintenance history data, enables optimization of the maintenance work cycle by defect probability by the applying Kaplan-Meier method.

Keywords: Spillway gate, Defect probability, Maintenance history data, Non-parametric probability model, Kaplan-Meier Method

1. BACKGROUND OF STUDY

The spillway crest gate is an important structure required to sustain reliable operability in the light of flood control.

Electric Power Development Co., Ltd. (hereinafter called "J-Power") has spillway gates aged over 40 years on average, and their components are deteriorating. J-Power is, therefore, attempting to ensure their reliability by understanding each degradation level based on data obtained through various checks and inspections.

The operation frequency of a spillway gate is much less than that of ordinary industrial machinery, and the timing and the time length of operation are determined by its locations, the weather and other variables. Moreover, there is constraint due to the generating operation, when the test and inspection involving the actual operation are carried out.

As mentioned above, there are many constraints to acquiring quantitative deterioration data of a spillway gate. Therefore, a supplemental evaluation method for the maintenance management is required.

In this study, the defect probability and maintenance cycle of spillway gate components were estimated by deterioration trend analysis and a statistical process for their past maintenance records.

2. BASIC CONCEPT

2.1. Statistical Analysis of Deterioration Trend

2.1.1. Framework and examination objects of analysis
In this study, the individual deterioration data of each spillway gate is not employed to determine a supplemental procedure for understanding its current condition. The statistical assumption method for the defect probability per spillway gate component, based on the maintenance history data, is applied.

The statistical analysis is roughly divided into parametric and non-parametric analysis.
Parametric analysis is a method of estimating the defect probability at any elapsed time on condition that the frequency distribution of the maintenance history data is

supposed to fit in with any theoretical probability distribution.

Non-parametric analysis is a method of estimating the defect probability directly on condition that the empirical distribution of the maintenance history data is assumed as a true value.

Parametric analysis has an advantage in being able to estimate the defect probability, only assuming the theoretical probability distribution and calculating the mean value, the standard deviation and so forth.

Meanwhile, it has a problem that the estimation accuracy becomes low, when the frequency distribution of the maintenance history data does not fit in with any theoretical probability distribution and/or there is insufficient data.

In this study, parametric and non-parametric analysis is applied in parallel so as to secure sufficient accuracy of estimation in accordance with procedure 1) to 4) as mentioned below.

1) The number of spillway gate components, which are replaced due to deterioration, is added up per elapsed period.
   Since it is difficult to discriminate the maintenance history data only, in this study, both replacements due to failure occurrence and due to deterioration without failure are presumed as replacement caused by the failure occurrence in this study.
2) Parametric analysis is performed by the widely used theoretical probability distribution, and the goodness of fit is examined.
3) When the goodness of fit by parametric analysis is insufficient, the study by non-parametric analysis is implemented.
4) Under the above procedure, the defect probability curves for each spillway gate component are established, and the period attained to the predefined threshold year is calculated. And the said period is assumed to be a standard value as the maintenance cycle.

This study examines radial gates and fixed wheel gates, which comprise the majority of spillway gates owned by J-Power. And, the examination objects are extracted from many spillway gate components by the following policies.

1) The failure or damage of components leads to decreased function of the whole equipment.
2) The cost and frequency of replacement is relatively high, therefore, optimization of the maintenance cycle contributes to the cost reduction.
3) As the number of specimens is sufficient to apply the statistical analysis, the examination objects are normal components of spillway gates.

The examination objects extracted according to the said policies are shown in Table 1.

Table 1. Examination object

Classification	Examination object
Gate leaf	Seal rubber
Hoisting device	Wire rope
	Motor
	Brake
	Reducer
	Control panel
	Position indicator

2.1.2. Parametric analysis

In order to comprehend the trend of the defect probability per spillway gate component and calculate assumption values in the period of data absence, the goodness of fit tests (Kolmogorov-Smirnov test and chi-square test) was performed to theoretical probability distributions widely used in the statistic, such as the normal, log-normal and Weibull distribution.

The example result, which assumes that the maintenance history data of position indicator fits in with the Weibull distribution, is shown in Fig. 1.

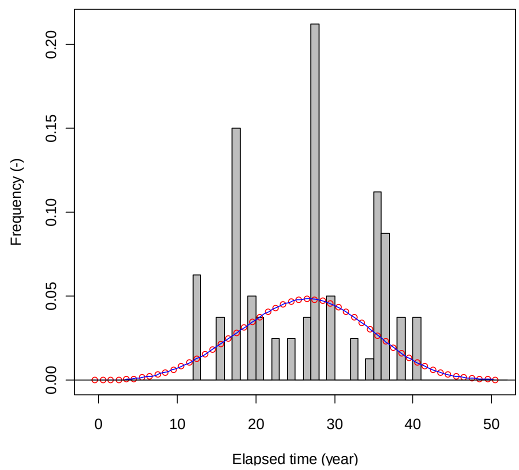

Figure 1. Comparison with frequency distribution of maintenance history data and Weibull distribution (Gate position indicator)

Figure 1 indicates that the maintenance history data have several peaks of frequency and its frequency distribution does not well fit it with the theoretical one. It is difficult to clarify whether this cause derives from the characteristic of the examination object having no particular peak due to an unexpected failure in the in-service period, or insufficiency of the sample number.

In order to quantitatively demonstrate the unconformable phenomenon, the goodness of fit test was performed by Kolmogorov-Smirnov test. The results are shown in Table 2.

There is a large disjunction between the distribution of the maintenance history data and the identified theoretical probability.

For the reason mentioned above, in this study, it is concluded that the parametric analysis is not suitable for trend estimation of the defect probability.

Table 2. Result by Kolmogorov-Smirnov test for frequency distribution of maintenance history data and theoretical probability distribution

Object	Theoretical probability distribution	Result of Kolmogorov-Smirnov test*)
Seal rubber	Normal	Fitted in
	Log-normal	Not fitted in
	Weibull	Fitted in
Position indicator	Normal	Not fitted in
	Log-normal	Not fitted in
	Weibull	Not fitted in

*) Significance level: 10%

2.1.3. Non-parametric analysis

The parametric model is a model that assumes that the data has come from theoretical probability distribution. In contrast, the non-parametric model is a model that does not rely on data and is made by the empirical probability distribution only from the observed data.

The Kaplan-Meier (hereinafter called "KM") method applied in this study is also a non-parametric analysis method.

The KM method has the advantage of applying to the more complicated distribution than the theoretical probability distribution by treating the empirical distribution curve as a true value (an actual distribution) based on the maintenance history data.

It is necessary that the defect probability should be built taking into consideration data that has an effect to the evaluation result (hereinafter called "censor data"), because it is supposed that there are some components still in-use at the time of observation censoring and that were censored by another cause except replacement in the observation period. In addition, there may be some errors of the data entry and adding up.

2.2. Treatment of Censor Data

Since many spillway gate components have been used for decades and the actual replacement records are limited, the ratio of censor data is estimated to be high. Therefore, the treatment of censor data is supposed to greatly impact the calculation result of the defect probability.

A comparison study for the treatment difference of censor data was implemented, and the results are shown in Fig. 2.

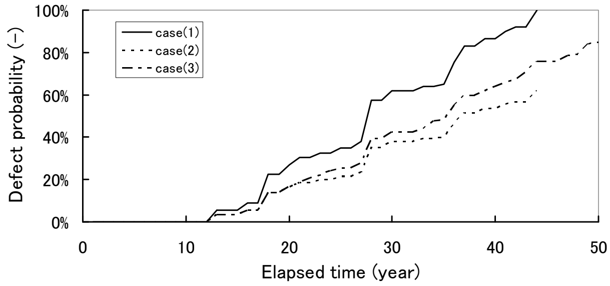

Figure 2. Comparison result for treatment difference of censor data (Gate position indicator)

Figure 2 is an example gate position indicator (Lateral axis: elapsed time, vertical axis: defect probability).

In this figure, cases (1), (2) and (3) are "KM distribution excluding censor data," "KM distribution without consideration of the censor data (assumption: the censor component does not break down in the in-service period (50 years) or the longest failure occurrence period observed)," and "KM distribution on condition that the non-failure occurrence period of censor data is supposed to be a period between the former failure occurrence and the observation censoring" respectively. The comparison of effect extent among them is shown in Fig. 2.

In case (1), the analysis accuracy is high, if the observation period is long enough and the maintenance history data reflects the actual situation of every replacement, even the component with an extremely long and short replacement interval. However, it is assumed that the replacement interval is short in excess compared to the actual situation due to the effect that the replacement interval is determined by only the renewal record of a component, which is replaced in a very short period in case the observation period from the commencement of in-service to the observation censoring is insufficient.

In case (2), since it is assumed that the censor component does not break down, the defect probability is generally low in excess.

For the spillway gate as an examination object in this study, since some components are supposed to break down in a few years and/or decades after the observation censoring, it is necessary to take into consideration the defect probability. In this study, the above treatment is reflected by case (3) "deduction from the number of examination object at each time of observation censoring."

The KM distribution is generally defined by the following formulas.

$$P(t) = 1 - \prod_{i=1}^{i\max}\left(1 - \lambda\left(\overline{t_i}\right)\right) \quad \text{......................................} \quad (1)$$

Where,

$P(t)$: Defect probability

$\lambda(\overline{t_i})$: Hazard function (Ratio function: the number of breakdown component during the time from t_{i-1} to t_i against the number of sound component at the time t_{i-1})

The hazard function has a variation due to the difference of censor data treatment as follows;

1) Method-1: KM distribution excluding censor data

$$\lambda(\overline{t_i}) = \frac{d(\overline{t_i})}{n(\overline{t_i})} \quad \text{......} \quad (2)$$

2) Method-2: KM distribution without consideration of the censor data

$$\lambda(\overline{t_i}) = \frac{d(\overline{t_i})}{n(\overline{t_{i-1}}) - s(\overline{t_\infty})} \quad \text{......} \quad (3)$$

3) Method-3: KM distribution on condition that the non-failure occurrence period of censor data is supposed to be a period between the former failure occurrence and the observation censoring.

$$\lambda(\overline{t_i}) = \frac{d(\overline{t_i})}{n(\overline{t_{i-1}}) - s(\overline{t_{i-1}})} \quad \text{......} \quad (4)$$

Where,

$d(\overline{t_i})$: Total number of failure occurrence observed in the time interval span $\overline{t_i}$

$n(\overline{t_i})$: Number of components without failure occurrence at the time $(i-1)\times\overline{t_i}$

$s(\overline{t_\infty})$: Number of censor data assumed that the breakdown occurs after the in-service period (for example; 50 years)

$s(\overline{t_i})$: Number of censor data that the failure occurs in the time span $\overline{t_i}$

Furthermore, the difference among Method-1 to 3 is explained collaterally by Fig. 3.

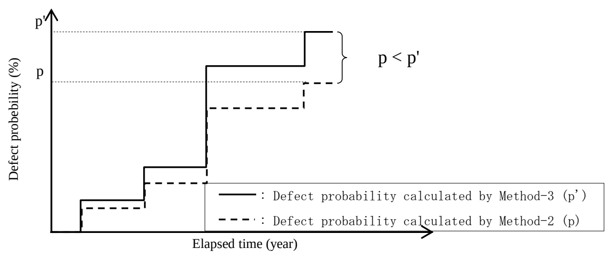

Figure 3. Difference of defect probability between Method-2 and 3 (Conceptual diagram)

The defect probability (p) calculated by Method-2 is the ratio that the replacement number is divided by the constant number of all examination objects until reaching the longest period of failure occurrence. On the other hand, the defect probability (p') by Method-3 is larger than (p) by Method-2, because the number of examination objects is deducted at each time of observation censoring in Method-3. In other words, the defect probability (p') by Method-3 is assumed to be a larger value.

The probability density distribution by parametric analysis is defined as a method of building the distribution based on the actual replacement data only, and classified into Method-1.

In the parametric model, the assumption by Method-2 is generally applied in many cases, when the censor data is taken into account. When the number of censor data increases, it is difficult to estimate the population parameter of the assumed theoretical distribution and the calculation also becomes complicated.

As mentioned above, it is understood that there is a restriction, when parametric analysis is applied to this study.

The result identifying the replacement data of the gate position indicator with the Weibull distribution is shown in Fig. 4. (As stated above, it was judged that there is no correlation by Kolmogorov-Smirnov test (significance level: 10%). Figure 4 is for reference.)

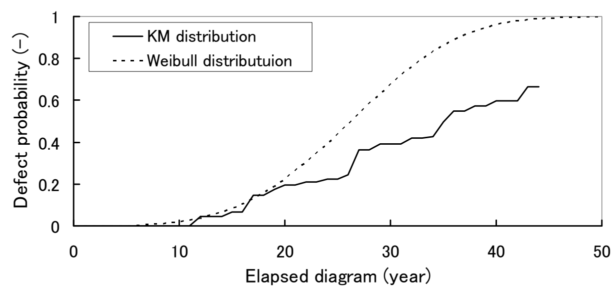

Figure 4. Comparison of defect probability between KM and Weibull distribution (Conceptual diagram)

Next, the selection of in-service components, which should be dealt with the censor data, was examined.

Figure 5 shows the specific designation procedure dealing with the censor data according to the result of the examination described above.

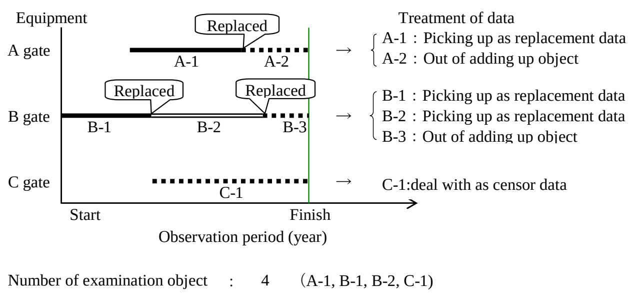

Figure 5. Specific procedure to deal with censor data (Conceptual diagram)

In the treatment of censor data, it considered that the calculation result is not separate from the actual situation by unnecessarily increasing the number of examination objects and excluding the recent replacement data. The following procedure explains the treatment of censor data.

1) If the examination object has a replacement record, all the replacement data is picked up and added up (A-1, B-1 and B-2 in Fig. 5), and the censor data from after replacement to observation censoring is neglected (A-2 and B-3 in Fig. 5).
2) If the examination object has no replacement record, it is dealt with as the censor data at the time of censoring (C-1 in Fig. 5).

Table 3 shows the number of examination objects according to the above procedure.

Table 3. Number of examination object

Object	Number of examination object		
	Replacement number	Censor data	Total
Seal rubber	198	17	215
Wire rope	128	23	151
Motor	102	32	134
Brake	106	53	159
Reducer	4	123	127
Control panel	120	33	153
Position indicator	91	58	149

In this study, since it is assumed that the number of censor data increases, analysis software that can handle the censor data "RCM Ver2.1.1 (developed by Central Research Institute of Electric Power Industry (hereinafter called "CRIEPI"))" was applied.

Among defect probabilities estimated in this study, for the period over the maximum failure occurrence time (section of no replacement record), the assumption value can be applied by the fitted curve that is established based on the annual defect probability of KM distribution.
However, there is a possibility of underestimating the assumption value of the defect probability due to the existence of censor data in which the elapsed time seems to be extremely long due to errors of data entry and adding up.
"RCM Ver2.1.1" applied in this study has a data screening function, which can remove the censor data after the maximum replacement period from the object data used for establishment of the failure occurrence prediction curve (hereinafter called "extrapolation curve"). This study is implemented through usage of this function.

3. ESTIMATION RESULT BASED ON DEFECT PROBABILITY CURVE

The maintenance cycle is defined as the threshold at which the defect probability, calculated by the non-parametric analysis, reaches a certain elapsed period. The calculation results for the maintenance cycle, according to this definition, are shown in Table 4.

Table 4. Period attained to threshold year

Object	Period (Threshold year)	
	Defect probability 30%	Defect probability 50%
Seal rubber	11	17
Wire rope	24	27
Motor	27	32
Brake	26	33
Reducer	40*)	43*)
Control panel	20	23
Position indicator	27	36

*) Threshold year by extrapolation curve

It is necessary that the threshold year should be determined as an allowable period taking into account the importance degree for each gate component and so forth. However, since this procedure is still at a stage under study at this moment, the periods attained to the defect probability 30% and 50% are indicated for reference in this paper.

Based on this procedure, the defect probability curve of gate position indicator is shown in Fig. 6.

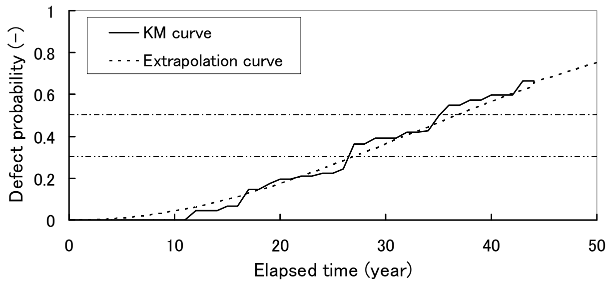

Figure 6. Estimation result of defect probability (Gate position indicator)

Although an extrapolation curve is shown for an entire period in Fig. 6, the value of the defect probability should be applied only in a section of period that has no maintenance history data, and the KM curve takes priority to the extrapolation curve in the other section of the period.
As the gradient of these curves indicates each trend of failure occurrence, it is comparatively easy to comprehend the maintenance cycle for a component having a steep gradient.
On the other hand, it is difficult to predict the failure occurrence for a component having a moderate gradient, and there is a possibility of a failure occurring shortly after the commencement of in-service. Therefore, daily inspection work becomes important to comprehend the condition of components.

Sustaining the function of each spillway gate component based on the defect probability curve, optimization of the maintenance method for the spillway gate components, such as a method combined with "Time Base

Maintenance (TBM)" and "Condition Based Maintenance (CBM)," is an issue in the future.

4. CONCLUSION

In addition to the daily checks and inspection works, to optimize the maintenance method in this study past maintenance records of spillway gate components were sorted out and reviewed.
Several maintenance cycles for the spillway gate component are estimated, establishing defect probability curves based on the deterioration trend analysis and statistical processing for the maintenance history data.

Since the goodness of fit by parametric analysis is low and the treatment of censor data needs to be considered separately, the availability by other analysis methods should be examined.
It was confirmed in this study that non-parametric analysis, such as the Kaplan-Meier method, is capable of analyzing the maintenance history records of spillway gate components.

J-Power is aiming to reflect this procedure in the specific plan of facility maintenance whilst expanding the applicable scope.
As the analysis accuracy and the maintenance history data are closely-linked, this procedure will be reviewed periodically while cumulating the maintenance history data.

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