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Updating Epistemic Uncertainty in Reliability Analysis for Pier Pile Stress Using Data in Construction and Maintenance Phase

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Abstract: It is becoming more and more important for society to plan and prioritize the repair and maintenance of existing infrastructures under budget constraint. The decision-making process is desirable based on the risk assessment of each facility, as suggested in ISO 2394. In analyzing reliability of a risk assessment, it is necessary to establish random variables with consideration of epistemic and aleatory uncertainties. In the reliability assessment of structures, many epistemic uncertainties, especially those assumed in design phase, can be reduced in the construction and maintenance phases.It would be more effective to re-evaluate the epistemic uncertainty of existing structures by using the information on materials and inspections delivered at construction or maintenance phase. This paper focuses on the pile stress verification of a pier, which is one of the typical structural types of port facilities. We discuss how information obtained in construction and maintenance phases can be reflected in the reliability analysis in several possible situations.

Keywords: epistemic uncertainly; construction phase;pier pile;reliability index.

1 Introduction

In developing repair plans for existing structures, prioritization should be based on budgetary constraints and other social constraints. This prioritization should be based on risk assessment, and reliability index for facility performance are often used as indicators of risk assessment (Vrijling et al.2011). The reliability assessment in such cases should deeplyconsider epistemic and aleatory uncertainties (ISO 2394. 2015).

In a previous study, a method using"survival information"has been proposed to reduce epistemic uncertainty in reliability assessment (Schweckendiek et al. 2014). In addition, a study has been conducted for a sheet pile mooring in the Port of Rotterdam to evaluate the reliability index of sheet pile stress during the service period by modeling the corrosion rate of steel in the harbor, applying the survival information based on a stability of the facility after construction. (Roubos et al. 2020).

In evaluating the reliability of such existing structures, the application of survival information described above is an effective method for reducing the epistemic uncertainty assumed in designs. In addition to this, by utilizing characteristics of existing structural members obtained at construction phase, such as data concerning the actual yield strength of steel delivered at the time of construction, the reliability of the structure can be evaluatedafter removing information that is obviously reasonable to delete from the epistemic uncertainty assumed at the design phase. On the other hand, such data are generally used only for quality confirmation in the construction phase of new facilities, and there are few examples of their application to structural performance assessment. To effectively plan repair projects utilizing risk assessment of existing structures, we recognize the importance of a framework to continuously track the reliability of structures by updating the information on uncertainties assumed in the design phase with the information obtained in the construction and maintenance phases.

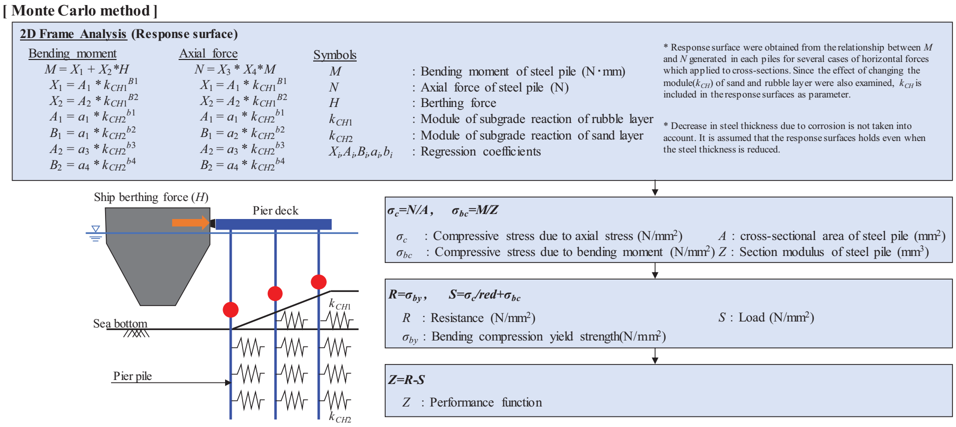
In this paper, as a basic study to establish this framework, we present the results of the reliability evaluation by updating the epistemic uncertainties assumed in the design phase regarding the yield stress of pier piles to the available information in the construction phase, using the stress verification of pier piles during ship berthing as an example. In addition, we present the results of a time-series analysis of the reliability index β based on the assumption of the corrosion rate of steel obtained in the maintenance phase, and also the effectiveness of reflecting data obtained in the construction phase in the reliability analysis of actual structures.

2 Reliability Analysis Method for Pier Pile Stresses in Japanese Technical Standards for Port Facilities

2.1 Reliability Analysis by Application of Response Surface Method

In the Technical Standards and Commentaries for Port and Harbor Facilities in Japan (OCDI.2018, TSPHF hereafter), the partial factor method has been introduced for stress verification of pier piles during ship berthing, and the partial factors were determined by reliability analysis based onMCS (Takenobu et al.2017). In the reliability analysis in this paper, we applied that analysis method to the study. The method is briefly described below.

Generally, the design of piers in TSPHF uses a two-dimensional frame analysis for the pier cross section as shown in Figure 1 to verify the stresses by using bending moments and axial forces generated by the action for the piles. In the reliability analysis, probability of exceeding yield stress of a steel pipe pile is calculated by MCS after setting the probability variables for the design parameters. In this case, a performance function for the stresses of the pile must be set, but such a function cannot be easily formulated for this type of frame analysis. For this reason, the performance function related to the stress of the pile is formulated in advance using the response surface methodology, and MCS is performed on the function to calculate the probability of failure. The ship berthing force is modeled as being transferred to the pier superstructure by the reaction force of the fenders.



* Response surface were obtained from the relationship between M and N generated in each piles for several cases of horizontal forces which applied to cross-sections. Since the effect of changing the module(k_{CH}) of sand and rubble layer were also examined, k_{CH} is included in the response surfaces as parameter.

* Decrease in steel thickness due to corrosion is not taken into account. It is assumed that the response surfaces holds even when the steel thickness is reduced.

Figure1. Reliability analysis method using response surfaces for pier pile stresses for ship berthing and conceptual diagram of virtual cross section

2.2Random Variables for Reliability Analysis

The random variables and their statistical properties used in the analysis in this study are listed in Table 1. The random variables set for this verification item are the ship berthing force, the yield stress of the pier piles, and the module of subgrade reaction. In the evaluation of ship berthing force, ship characteristics are also considered as a random variable. All these values are used for code calibration in the TSPHF. These values are used to obtain the berthing energy of the vessel (E_f), and the value of ship berthing force(H) in Figure1 is obtained using a separately formulated relationship between berthing energy and fender reaction force. The evaluation of berthing energy is as shown in Eq. (1), and the relationship between berthing energy and fender reaction force is modeled as shown in Figure 2.

Table 1.Random variables and their statistical properties in this study

Random variables		Characteristic value X_k	Mean bias μ/X_k	Coefficient of Variation	Types of distribution
Module of subgrade reaction of rubble layer k_{CH} (kN/m^3)	Sand layer	7500	1.333	0.76	Lognormal
	Rubble layer	3500			
Berthing velocity V_b(m/s)		* See attached below table			
Virtual mass factor C_m					
Eccentricity factor C_e					
Yield strength σ_y (N/mm^2)		235	1.2	0.09	Normal

Random variables	Characteristic value X_k	Mean μ or Median M_e	Standard deviation	Types of distribution
Discharge tonnage of ships (DT)	5,870	5,695	260	Normal
Berthing velocity V_b(m/s)	0.1	0.061	0.034	Lognormal
Virtual mass factor C_m	2.118	1.77	0.105	Normal
Eccentricity factor C_e	0.665	0.62	0.023	Normal

$$E_f = \frac{1}{2} M_s {V_b}^2 C_m C_e \tag{1}$$

Where inEq. (1),M_s, V_b, C_m, $C_e$are defined as in Table 1.

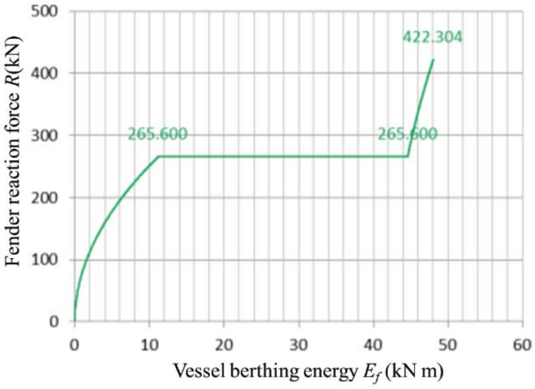


Figure 2.Calculation model between vessel berthing energy$E_f$and fender reaction force R (Modified for Takenobu, 2017)

2.3RandomVariables that can be Updated after Design

When evaluating performance of actual pier steel pipe piles for ship berthing by using reliability indexes for the stress of steel pipe piles, it should be noted that the random variables and their statistical properties summarized in Table1 are only settings for design phase. Since such random variables are assumed as epistemic uncertainties at the time of design, it is necessary to update the information that can be changed after the design is completed before evaluating the reliability in the performance assessment of the actual structure.

In this case, examples of information that can be changed after the design, i.e., information that can be reduced uncertainty are: 1) Measured values of vessel berthing speeds at the pier; 2) Yield stress of steel pipe piles delivered at the construction phase; 3) Loading tests at the construction phase, and more, to evaluate *N* values and ground spring values. In the following, we present the results of a trial calculation of the effect on the reliability analysis results of updating the yield stress of the pier piles assumed in the design phase to the yield stress delivered in the construction phase, as shown in 2) in the above example, for a pier set up as a hypothetical cross section as a basic study.

3 Yield Stress of Pier Piles that can be Obtained atConstruction Phase and its Application to Reliability Analysis

3.1Uncertainty about Setting of Analysis Section and Yield Stress of Steel Pipe Piles

The cross-section analyzed was a pier with three rows of piles driven in the cross-sectional direction in the sea and land directions, as shown in Figure3. This cross-section is a hypothetical cross-section, and the pile specifications, such as pier wall thickness and diameter, are set to just satisfy the TSPHF.

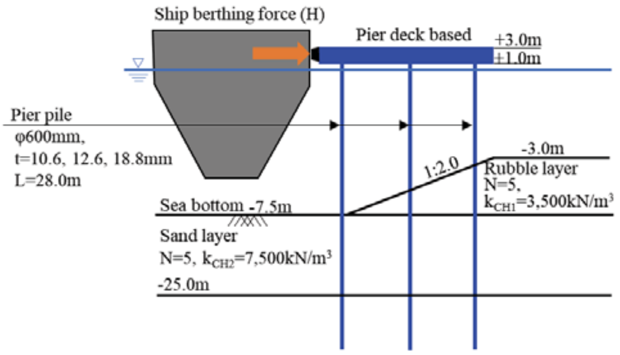


Figure 3. Virtual cross section used in the study

The yield stress of steel pipe piles (design phase) as a random variable has a bias between characteristic value and mean value, as shown in Table1, and a coefficient of variation of 0.09 is set for the mean value. This value is set based on data on yield stress of steel pipe piles throughout Japan and can be interpreted as indicating epistemic uncertainty regarding yield stress at the design phase.

3.2Yield Stress in Construction phase and Handling in Reliability Analysis

In Japan, it is common practice for the contractor to submit a "mill sheet" to the client for quality verification of the steel pipe piles to be installed at the pier. Assuming that this information is reflected in the yield stress of steel pipe piles in the hypothetical cross section shown in Figure 3at the construction phase, we use this information to update the reliability of the stress of pier steel pipe piles for ship berthing. Specifically, the authors update the yield stresses of the hypothetical cross sections set at the design phase based on the yield stress values of the actual mill sheets of steel pipe piles obtained separately by the authors (the number obtained is 42). Figure 4 shows the histogram of the yield stress of the mill sheet used in this study (hereafter referred to as “yield stress after construction”) superimposed on the distribution of the yield stress of the steel assumed in the design. The yield stress after construction is at least 1.5 times higher than the characteristic value of yield stress at the design phase.

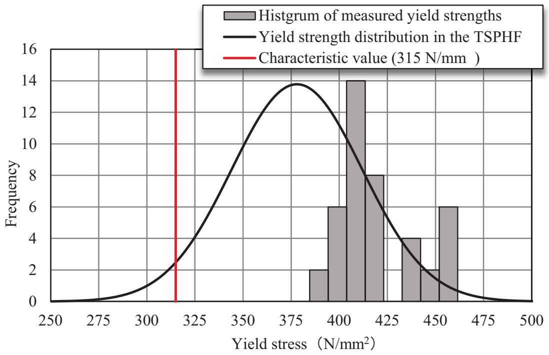


Figure 4. Comparison of the histogram of yield stress after construction used in this study and the distribution of yield stress assumed in the design phase

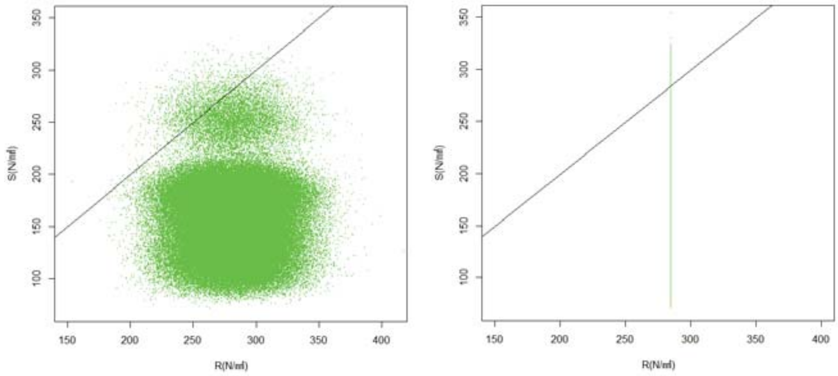


Figure 5. Comparison of *R* and *S* distributions for pile stresses analyzed (one case is selected from results.) Left: Assumption at design phase.Right: Stress of steel pipe pile at construction phase updated according to the information in the mill sheet. (Uncertainty is eliminated, so it does not spread to the *R* side.)

Basically, the relationship between pile position and the mill sheet corresponding the pile is one-to-one correspondence, but some facilities, especially old existing facilities, are difficult to have that detailed information.

Tograsp the influence of such cases on the reliability analysis results, reliability analysis was conducted for cases that considering all combinations (= $_{42}P_3$=68,880 cases) of the available yield stresses for the three rows of pier piles modeled as shown in Figure3, and the variation of the reliability indexes was examined. If the correspondence between the location of the installed steel pipe pile and the delivered mill sheet is accurate, one of these results can be identified and extracted. For the reliability analysis, the method shown in Figure1 was applied to each of the three piles in the hypothetical cross section, and the min. value of these $\beta$was treated as the reliability index β in each case.

The only parameter for which information such as uncertainty was updated in this paper was the yield stress, and its value was treated as a definitive value. Figure 5plots the results of the MCS-based reliability analysis in *R*-*S*space (definition of *R* and *S* are in Figure 1); the characteristic distribution on the *S* side reflects the characteristics of the model shown in Figure 2regarding the relationship between berthing energy and fender reaction force. In addition, only the parameter related to the steel yield stress exists on the *R* side of the steel pipe pile. Therefore, when the yield stress is set to a definitive value, the data is not distributed on the *R* side of the pile.

3.3Calculation Results of Reliability IndexWhen Considering Yield Stress Obtained atConstruction Phase

Figure 6 compares the reliability index for the stress in pier piles when the yield stress distribution assumed in the design phase is applied and when the yield stress after construction is as a definitive value. Since multiple reliability indexes are obtained for the case where the yield stress after construction is applied, depending on the number of calculation cases, a histogram of the latter reliability index was presented.The histogram of construction phase shows a complicated shape, which may be influenced by the histogram of yield stress shown in Figure 4.

The reliability index tends to increase compared to the results of the design phase because the yield stress after construction is higher than the average value assumed in the design phase and because of treating the yield stress as a definitive value (eliminating the epistemic completely). However, the range of β depends greatly on the value of the yield stress after construction, resulting in a variation of about 2as the calculated β. This effect will be discussed again later, as it has a significant impact on the results of the time-series reliability analysis presented below.

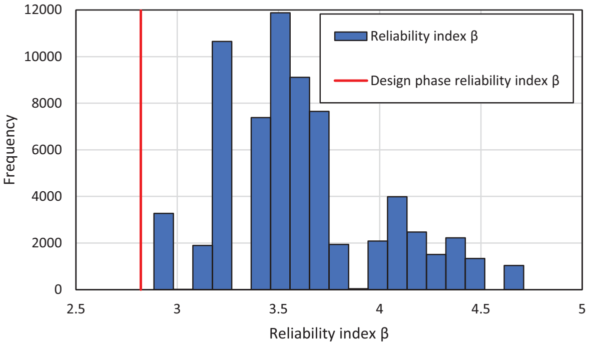


Figure 6. Results of evaluation of reliability index when yield stress after constructionare applied.

4 Application of Time-Series Reliability Analysis for Stresses in Pier Steel Pipe Piles

4.1Analysis Method

After the above reliability analysis was conducted on the hypothetical cross section in Figure 3, the reliability index of the steel pipe pile stresses after the design phase of the pier were evaluated chronologically by calculating the thickness reduction of the steel pipe piles after setting the corrosion rate in the port. In the previous study(Robous et al,2020) attempts have been made to determine when repairs and other measures are necessary through this type of analysis, and the time-series evaluation of facility performance is a useful evaluation method for decision-making in facility repair planning.

When considering the yield stress after construction, this information was applied at year 0 for analytical convenience. The reliability index was then examined by decreasing the thickness of the steel at each step based on the corrosion rate, with one year as the first step. Although it is known that the reduction in thickness of pier piles is relatively large in the splash zone, the same corrosion rate was applied to the pier piles in the depth direction to simplify the calculations here. This bold assumption is because deterioration of steel pipe piles' thickness to depth direction is not considered when creating the response surfaces shown in Figure 1. Therefore, the calculation results were used only to identify general trends.

4.2Discussion of Results

Figure 7 shows the results of the analysis. The black line in the figure shows the calculation results using each random variable in the design phase (Table1), and the yellow line shows the reliability index plotted in a time series by extracting only the combinations of values with the max.or min. reliability indexβ in Figure 6, considering the yield stress after construction. The purple squire marks are the value of each β at construction phase, which is corresponding toFigure 6. Since the corrosion rate may be smaller than the rate assumed in the design, a corrosion rate of 0.02 mm/yearis also shown in the figure (orange line). Furthermore, the reliability index (the probability variable is the same as in the design phase.) corresponding to the thickness of steel pipe piles after 50 years(Red dotted line in Figure 7.), which is the typical design service period of port facilities in Japan, is shown in the figure, assuming the decision criteria when some repair of the pier piles is necessary. The relationship of β to the elapsed time is not a constant rate of decrease, but rather a characteristic curve, which is strongly influenced by the characteristics of the distribution on the load side as shown in Figure 2.

When the yield stress after construction is applied to the reliability analysis, the higher reliability index in the construction phase is reflected, and the time until the reliability index falls below the threshold is slower than assumed in the design phase, even if the corrosion rate is the same. This suggests that incorporating information from the construction phase into the performance evaluation of the facility may allow for more rational planning of repairs. However, the period before the value of the reliability index falls below a set threshold has a considerable range depending on the status of the yield stress after construction phase. This implies that if the traceability of the properties of steel pipe piles at the construction phase is not sufficient, the result is that many uncertainties must be considered when planning the repair of the facility. Therefore, from the viewpoint of post-design facility performance evaluation, it is important not only to understand the material properties at the time of construction, but also to ensure traceability regarding its spatial information.

As shown in the figure, the effect of corrosion rate on the reliability index value is significant, and continuous monitoring and appropriate modeling of corrosion rate during the maintenance phase are also important factors in evaluating facility performance.

The combination of "survival information" as described in the beginning of this paper and reliability evaluation using information other than yield stress of steel, which was not treated in this paper, are issues to be considered in the future for further rationalization of facility performance evaluation.

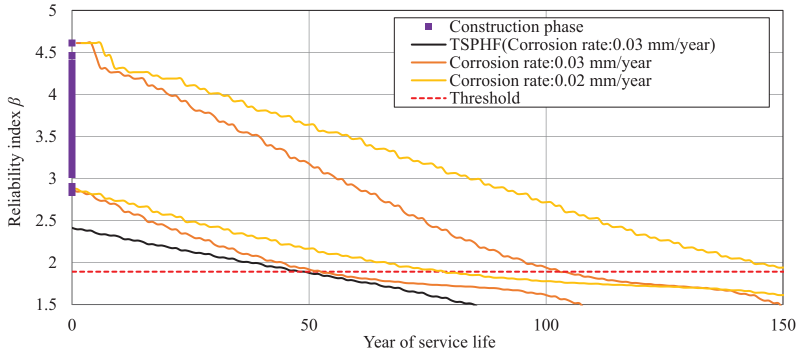


Figure 7. Comparison of time-series analysis results for $\beta$for stresses in pier steel pipe piles

5 Conclusion

In this paper, as a basic study for effective planning of repair plans based on risk assessment of actual structures, the effectiveness of updating the uncertainties assumed in the design phase to the information available in the construction phase and reflecting them in the reliability analysis is discussed, using the stress verification of pier steel pipe piles during ship berthing as an example. The main conclusions are as follows:

1) In the stress verification of pier steel pipe piles, by updating the yield stress of steel pipe piles to the information available at the construction phase, it is possible to remove the epistemic uncertainty and to evaluate the reliability index related to the verification more reasonably.

2) The results of the time-series evaluation of the above reliability index suggest that if the characteristics of the piles delivered at the construction phase and the spatial location of the piles are not known one-to-one, the uncertainty regarding the time to reach the threshold of facility performance from the start of facility service will be high. Therefore, in order to effectively plan the repair of actual structures, it is important not only to understand the characteristics of the materials used, but also to ensure spatial traceability.

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