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Reliability Assessment for Residual Bearing Capacity of a Railway Bridge Foundation after Scouring

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Abstract: In Torrential Rain in Northern Kyushu region in Japan in July 2012, the foundation of a railway bridge across a small river settled approximately 0.3 m because of scouring. In this study, detailed investigations or tests, and simple repairs (jacking up of girders and track maintenance) were performed, and the slow-speed train service resumed approximately a month following the incident. Changes during this period in the reliability of the bridge bearing capacity were assessed by Bayesian updating with a particle filter. Five steps, which are outlined as follows, were used for reliability assessment: Step 0—a regular inspection period approximately one year before the damage, Step 1—immediately before the damage (outflow of overburden), Step 2—immediately after the damage; Step 3—boring inspections (increased reliability of the ground information), Step 4—tests with 90% static train loading (increased reliability of the bearing capacity), and Step 5—train running test (increased reliability of the bearing capacity). The calculation results quantitatively indicated that the reliability index β decreased because of the damage and that the parameter value increased with more information, which revealed the validity of the engineering decisions during the damage restoration periods. It is expected that weather hazards will intensify in the future. Hence, the present findings can be used in the rapid recovery of structures that are subject to similar damage.

Keywords: Reliability assessment, residual resistance, bridge bearing capacity, railway bridge assessment.

1. Introduction

It is required that structures with high social significance (e.g., railways and roads) are repaired in a timely manner such that their operations can resume immediately after they have been damaged by heavy rains or earthquakes. The resistance of the structure following the disaster must be rapidly evaluated to immediately resume operation. In the past, this residual resistance was empirically assessed by highly skilled engineers, who determined whether the structure should be restored, and what course of action should be taken for its repairs, and reliability-based assessments were not conducted.

The present study conducts a reliability assessment of residual resistance following these types of disasters. Particularly, we use the case study of a railway bridge foundation, which settled because of scouring. The slow-speed train service resumed on the bridge after various inspections, and repairs were conducted after the disaster; this steadily increased its qualitative reliability. We quantitatively assessed the reliability of the residual bearing capacity of the railway bridge foundation for a duration from before the disaster to the resumption of operations.

2. Target structure and overview of scouring damage

The target case study was a railway bridge across a small river. Its pier's shallow foundation, which rested upon a cobble stone-mixed gravel ground, was subject to significant scouring damage (settlement and tilting) caused by the Torrential Rain in Northern Kyushu region in July 2012 (Kuroki et al., 2018). The state of the damage is shown in Figure 1. Immediately after the disaster, it was presumed that it will be necessary to remove and rebuild the damaged pier, because such a large residual deformation was observed that it was assumed that the train could not safely run across the bridge.

Structural specifications of the damaged pier are shown in Figure 2. The oval-shaped piers supported steel girders with a length of 9.8 m and were supported by a shallow foundation with rectangular footing (4.05 m x 2.15 m). These specifications had not changed since the bridge was constructed in 1931 (approximately 80 years before damage).

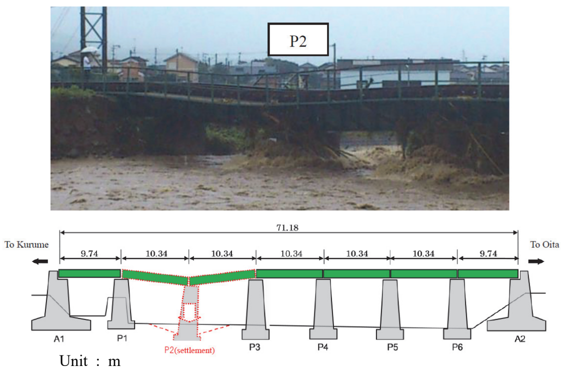


Figure 1. State of damage

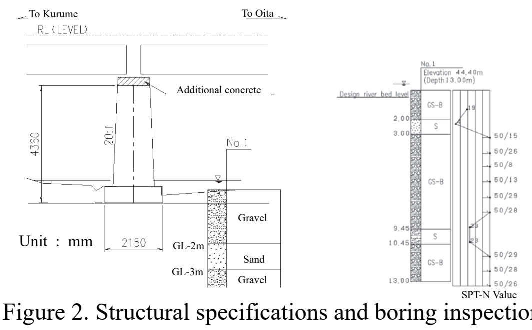


Figure 2. Structural specifications and boring inspection results of the damaged pier

The post-damage measurement results indicated that the pier settled approximately 300 mm and developed a tilt of approximately 49/1000 and 21/1000 rad in the upstream and track terminus directions, respectively. Subsequently, boring inspections were planned. However, due to the restrictions on the installation location of the boring machine, the boring inspections of the ground could not be conducted directly under or immediately beside the damaged foundation. As such, they were conducted at the halfway point to the next pier (5 m away from the center of the damaged foundation). According to the boring data, the average SPT-N value in the range of altitude of 3 m downward from the bottom of the footing was 25.

Additionally, based on the visual inspections conducted after the water level started decreasing, it was confirmed that there were no large voids by local scouring near the foundation, and that some of the soil on the side of footing remained in place. It was determined, as a result of the measurement, that the minimum embedded depth D_f of the footing perimeter was approximately 200 mm.

Percussion tests were also conducted to determine the soundness of the damaged pier. Percussion tests are methods that determine the natural frequency of structures using a weight to strike the pier's upper end to stimulate the structure's free vibration. The natural frequency of structures decreases when the performance of the foundation's bearing capacity and the soundness of its constituent components decreases. The percussion test is widely adopted in the Japanese railway field as a quantitative method of soundness evaluation. One year before this disaster and immediately after this disaster, the percussion tests were carried out, and the natural frequencies were compared. The decreasing rate of natural frequency as a result of this disaster was comparatively small. According to the maintenance standard of a Japanese railway structure, this minor decrease in the rate was judged as a "Slight deterioration."

Based on these results, the damaged pier was considered to have settled and tilted because of outflows in the overburden soils of the side and upper footing, and erosion (removal of only small diameter soil particles) of the base ground under the bottom of the footing. However, there was still some expectation that the subgrade at the base of the foundation would react because the large diameter soil particles (cobble stones and gravel) were in contact with the bottom of the footing. Hence, the temporary remediation approach shifted from removal and reconstruction of the damaged pier, to re-using the damaged pier after emergency restoration. It was hoped that the change to this policy could shorten the train suspension period.

However, it was assumed that the reduced D_f and the erosion have reduced the bearing capacity of the damaged foundation. Since the boring inspection could not be performed in the immediate vicinity of the damaged foundation, the bearing capacity estimate was considered unreliable. Additionally, because the Japanese maintenance standard was intended originally for daily maintenance (i.e., when the residual displacement has not occurred), the "Slight deterioration" result of this standard based on the percussion tests was considered insufficient evidence to rely on for the decision to temporarily resume the train operation. Therefore, static vertical loading tests and train running tests were additionally conducted to further ensure the reliability of the foundation's bearing capacity performance.

3. Residual bearing capacity inspections and test s

3.1 Vertical loading test

The main objective of a vertical loading test was to demonstrate that the damaged foundation exhibited a bearing capacity performance that could withstand the train operation. Another objective was to predict the magnitude of additional residual displacement that would occur after emergency repairs such as jacking up and track maintenance.

The loading method consisted of placing two steel water tanks on girders and filling the tanks with river water up to a load of 520 kN, which corresponded to approximately 90% of the heaviest trainload. However, even if 520 kN was loaded on the girders, the applied load on the base of the damaged foundation was only 395 kN.

The results of the time history of the settlement and tilting degree and the load-displacement relationship is shown in Figure 3 and 4. The settlement and tilting degree values immediately before water was filled into the tanks were set as zero values.

The highest increment was observed during the first cycle for both settlement and tilting. However, cumulative changes were subsequently observed to some extent, with repeated loading. The final residual displacement was approximately 1 mm for the settlement, and 0.1/1000 and 0.6/1000 rad for the tilting degree in the upstream and track terminus directions, respectively. Both values were significantly lower when compared to those due to the scouring damage (i.e., 300 mm, 49/1000 and 21/1000 rad).

Therefore, this indicated that the pier exhibited satisfactory performance of the foundation bearing capacity for the train loading levels, and it was possible to conduct emergency repair work (for e.g., jacking up of

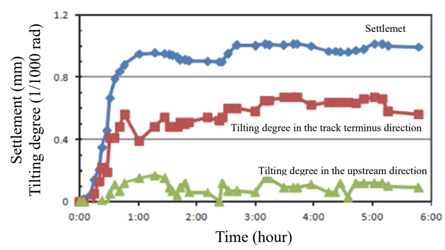


Figure 3. Static loading test results
(time history of settlement and tilting degree)

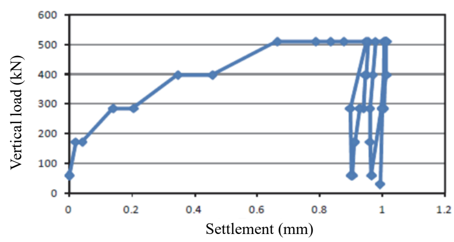


Figure 4. Static loading test results
(vertical load - settlement relationship)

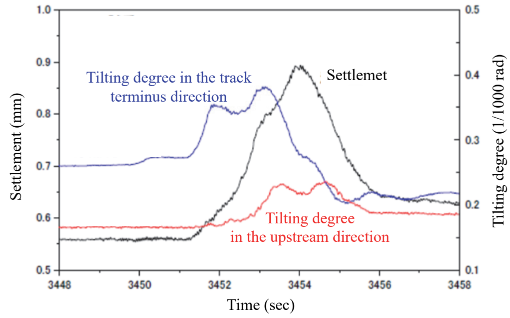


Figure 5. Example of train running test result (time history of settlement and tilting after the passing of a 25-km/h train)

girders, additional truss concrete, and track maintenance) and the subsequent train running tests.

3.2 Train running tests

Train running tests were conducted for the final safety confirmation before the resumption of regular train service. The test train was a diesel locomotive, which is the largest trainload on this bridge, and the maximum vertical load that acted on the damaged foundation was 450 kN.

As the result of the train running test, the time history of the settlement amount, and the tilting degree when a train travels at 25 km / h across the bridge, are shown in Figure 5. The settlement amount and tilting degree immediately before the first instance of the train passing were set as the zero values. The dynamic settlement was 0.3 mm, and the tilting degree was approximately 0.1/1000 rad (equivalent to 0.6 mm in horizontal displacement of rail) at half-amplitude when the train passed, and the values were sufficiently low relative to the track maintenance standard. The train test results indicated that when the train was at a slow speed, the foundation exhibited the required bearing capacity performance for train operation, and the pier was deemed re-usable.

4. Reliability assessments of the damaged foundation

4.1 Problem setup

Safety assessments based on reliability theory were conducted for the previously mentioned case study for the activities undertaken because of the scouring damage to the pier foundation and the emergency restoration. Reliability updates were conducted on the inspections and tests at each step, given the conditions of the target case study. We discussed engineering decisions during the actual activities and their effects on reliability levels.

It is noted that the objective of the present investigation did not involve tracing the process of the actual activities in detail. Conversely, it involved confirming the effects of introducing reliability theory and demonstrating that it can be useful in the actual work as well. Thus, the criteria value of reliability index in this research was limited to the verifications of vertical bearing capacity until the resumption of the temporary train operation, and several assumptions were adopted to simplify the problem.

The external applied force S used in the assessments was set as the vertical load acting on the base of the foundation and was the sum of the dead load W_D (due to the bridge pier and girders) and live load W_L. The live load W_L was set as the sum of the train load and impact load. The impact load was set as dependent on each of the train speeds during slow-speed and standard-speed operations based on a design standard for Japanese railway structure. The dead load is a deterministic value and the live load is a lognormal distribution.

Furthermore, the resistance R was the design value of the bearing capacity, which was the ultimate bearing capacity of the shallow foundation divided by the safety factor F_s.

The ultimate bearing capacities were calculated based on the design standards for Japanese railway structure using Terzaghi's theory, which varies depending on the embedded depth D_f. The Terzaghi's bearing capacity coefficients N_γ and N_q were theoretically translated from the internal friction angle ϕ, which was empirically estimated from the SPT-N value. The safety factor was set at $F_s = 2$. This value is typically used in the design of railway structures in Japan. This safety factor has two purposes, to prevent the occurrence of large displacements for safety during the train running, and to provide an empirical margin for the uncertainty of the bearing capacity estimation.

An overview of the investigation steps to perform the reliability analysis and the assumed basic variables is shown in Table 1. The embedded depth D_f was treated as a determined value as opposed to a random variable because these were measured during actual investigations.

Table 1. Overview of basic variables

Step number for reliability assessment	Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
	Prior inspection (one year before)	Outflow only overburden (virtual)	After scouring and erosion	Boring inspection	Static loading test (equivalent to 90% of train load)	Train running test
Dead Load W_D	600 kN					630 kN
	Deterministic value (COV = 0%)					
Train operation	Normal train operation		Train speed restricted to slow			
Live Load W_L	Mean : 560 kN		Mean : 490 kN			
	Lognormal distribution, COV = 30%					
Embedded depth D_f	2.1 m	0.3 m				
	Deterministic value (COV = 0%)					
SPT-N value of bearing ground	Mean :30		0-30	Mean :25		
	Lognormal distribution COV = 30%		Uniform dist.	Lognormal dist. COV = 45%		
Calculated model error	Mean of “measured / predicted value” = 1.0					
	Lognormal distribution, COV = 30%					
Likelihood function for Bayesian updating				Distribution of SPT-N value estimated by boring inspection	Two-stage distribution with assurance load by survival analysis shown in below	
					1005 kN	1100 kN

Moreover, to simplify the problem, the eccentricity or tilting effects of Terzaghi's theory were ignored, the water level was fixed to the underside of the footing, and the dead weight on the footing was ignored. The concept of each reliability assessment step is explained below.

4.1.1 Step 0: Regular inspection before the damage
One year before this disaster, the result of the visual inspection was sound. In other words, it can be considered that the ground on the bottom of the foundation had not changed since it was constructed until the time of this disaster. In the history of railway structures construction in Japan, there is an empirical rule that the minimum SPT-N value of the sandy or gravelly ground to which shallow foundation can be applied is 30. Additionally, it is generally known that variations in SPT-N values can be represented by a lognormal distribution. Therefore, in this study, the SPT-N value of bearing ground was modeled by a lognormal distribution with a mean of 30. Its coefficient of variation COV was assumed to be 30% for convenience.

4.1.2 Step 1: Outflow only overburden (virtual)
This step is a virtual step for reliability assessment when significant damage has not occurred. It is assumed that the flood was only stopped by the outflow of the overburden (i.e., the decrease of the embedded depth D_f), and the train operation resumed after checking the track at the normal water level.

4.1.3 Step 2: After scouring and erosion
This step corresponds to the condition immediately after the damage and was characterized by the occurrence of significant settlement of the foundation and suspected decrease in strength (i.e., SPT-N value decreases) due to loosening of the ground owing to the scouring and erosion of the soil at the bottom of the foundation. Hence, it was assumed that a distribution of the SPT-N value changed the uniform distribution ranging from 0 to 30.

4.1.4 Step 3: Boring inspections
This step corresponded to the condition where the uncertainty of the SPT-N value was reduced compared to Step 2 due to the boring inspections, as shown in Figure 2. The distribution of the SPT-N values at this step was determined by the following Bayesian update. The prior distribution of the SPT-N values was the uniform distribution in Step 2. Bayesian updating was performed on this prior distribution with the likelihood function of a normal distribution whose mean is $N = 25$. However, the COV of the likelihood function was assumed to be 0.45, which is 1.5 times that of Step 0 (before the disaster), considering that the position of the boring inspections was approximately 5 m away and that a weak sand layer was interposed.

4.1.5 Step 4 and 5: After loading and train running tests
Step 4 was designated as the end of the static loading tests (Figures 3 – 5) that used water tanks. Step 5 was designated as the end of the train running tests (Figures 6 – 7) that used maximum train loads. The resistance R (design value of bearing capacity) was determined using Bayesian updating. Details on the Bayesian updating process used in Step 4 and Step 5 are subsequently discussed.

4.2 Reliability assessment method
4.2.1 Response surface method
The ultimate bearing capacity of the shallow foundation can be calculated based on railway design standards, although this is considerably complex when conducting reliability assessments. Thus, we conducted a parametric study analysis that was limited to the applicable structural elements and was related to the embedded depth D_f (m), the SPT-N value, and the resistance R (kN) of the foundation base ground using regression analysis. The response function (Figure 6) was referred to as the response surface.

The response surface obtained from regression analysis using data values of $N = 10 – 35$ and $D_f = 0 – 2.1$ m is as follows.

$$R \approx R_{est} = a\, e^{bN}, \tag{1}$$

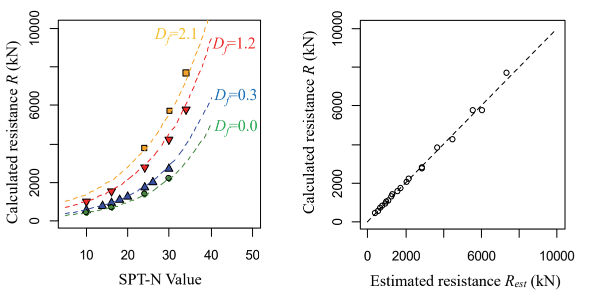
$$a = 247\, D_f + 185, \tag{2}$$

$$b = 0.0821 - 0.0063\, D_f. \tag{3}$$

However, since the calculated model error is not included in equation (1), it was added to the lognormal distribution separately in the reliability assessment.

4.2.2 Bayesian updating with the particle filter method
In this study, Bayesian updating using the particle filter method was applied for the reliability updating of the target structure. Depending on the field conditions (qualitative information) and additional observations (quantitative information), specific reliability updating processes were performed employing the above response surface equation. The details relevant to the updating process are described below. It should be noted that the use of mathematical descriptions and basic variables is avoided in this paper, as the discussion is focused on whether reliability updating can improve safety management practices. Please refer to the relevant literature (e.g., Schweckendiek et al., 2014).

4.2.3 Assurance load by survival analysis
From the results of the loading and train running tests described in the previous section, the residual displacement was small enough for the train operation to resume. These tests assured that the resistance of the foundation, which was previously unknown, exceeded at least the maximum load applied in the test. In other words, the maximum load of the test can be interpreted as the “assurance load.” In Step 4 and Step 5, Bayesian updating



a) Calculated result by design standard b) Result of response surface methodology

Figure 6. Response surface to calculate designated vertical bearing capacity

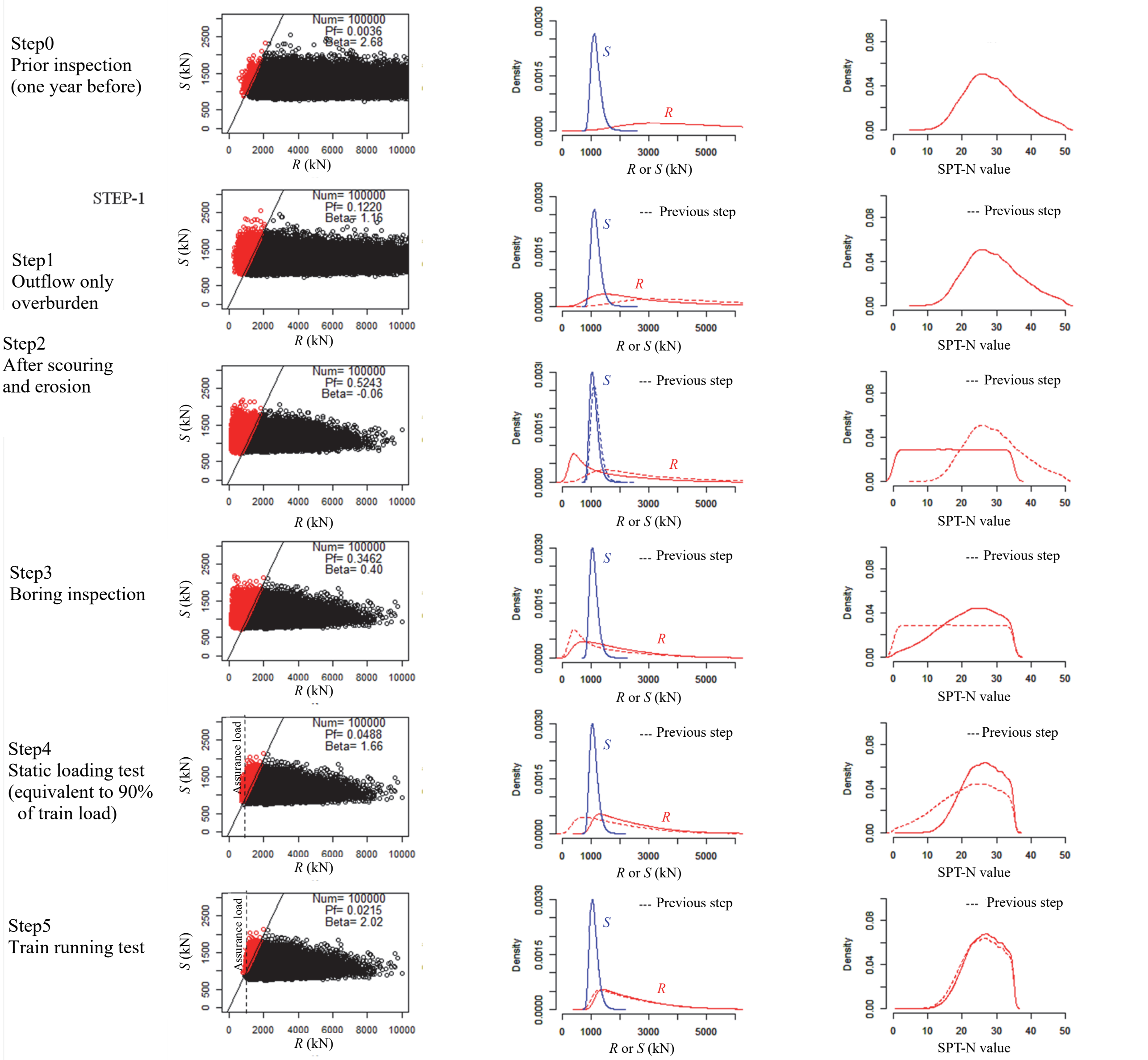
was performed based on a concept called "survival analysis" to express the assurance load stochastically (Schweckendiek, 2011).

According to the concept of the assurance load by survival analysis, the likelihood function used for Bayesian updating was set to a two-stage distribution shape in which the probability was zero when the load was smaller than the assurance load. Here, the probability had a uniform distribution when the load was larger than the assurance load.

Particularly, the value of the assurance load in Step 4 was 1005 kN, which is the sum of the dead load and the reaction force at the bottom of the foundation by the water tank. In Step 5, in addition to the train weight, the weight of the concrete used for the repair and the impact load (reduced to half of the design value assuming the maximum speed) were added, and the assurance load was increased to 1100 kN.

5. Analysis results and discussion

In Figure 7, a scatter plot of the external applied force *S* and resistance *R* (Figure 7(a)), the probability density of *S* and *R* (Figure 7(b)), and the probability density of the SPT-N values (Figure 7(c)) are shown for each step. Additionally, the interquartile range of *S* and *R* is shown in Figure 9, and the changes in the fluctuation range are given for each step. The transitions of the reliability index β as calculated for each step are also shown on the right axes of Figure 9. The fluctuation range of the resistance *R* significantly exceeded that of the externally applied force S in the present investigation, and this demonstrated that updating observations on the durability and resistance significantly contributes to improvements in reliability.



a) Scatter plot of *R* and *S* by MCS results   b) Probability density of *R* and *S*   c) Probability density of SPT-N value

Figure 7. Reliability assessment results for each step

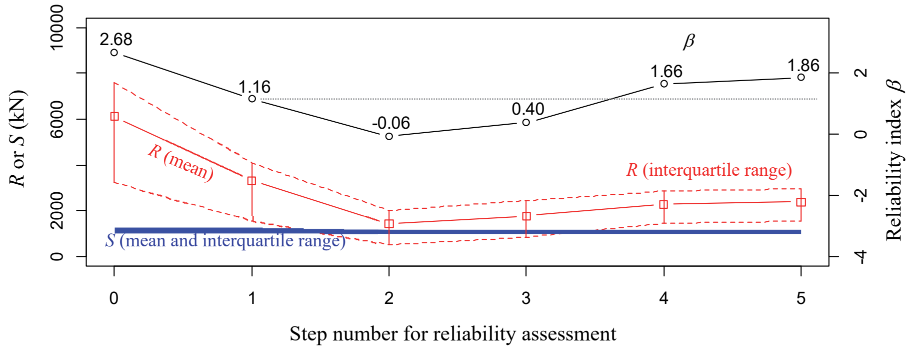


Figure 8. Transitions in external applied force S, resistance R, and reliability index β for each step

In Step 0, the reliability index β was calculated as 2.68. This value can be regarded as adequate, as the foundation has safely supported train loads for over 80 years.

In the virtual Step 1, the SPT-N value does not change; however, the embedded depth D_f is decreased, and the reliability index is decreased to $\beta = 1.16$. Assuming that this virtual situation actually occurs, it is expected that normal train operation resumes because there is no residual displacement, and the track inspection can satisfy the operation standards. A decrease in D_f will be detected at the next two-year periodic inspection. After that, repairs (such as restoration of D_f) are performed, and the original (Step 0) β is restored. In other words, the value of β in the virtual Step 1 is practically acceptable in the short term (less than 2 years) and is one of the indicators for determining the possibility of emergency recovery and operation restart after a disaster.

In Step 2, significant residual subsidence occurred (see Figure 1), and the bearing capacity may have been reduced by erosion of the ground under the foundation. However, since the information on the ground has not been obtained yet, the strength is smaller than that in Step 0, and the distribution of the SPT-N values was reduced to a uniform distribution from 0 to the mean value of Step 0 ($N = 30$). Because β for the slow trainload was a small value ($\beta = -0.06$), the train could not resume operation.

In Step 3, the effect of improving the reliability of the bearing capacity of the foundation by low accuracy boring inspections conducted at 5 m away was evaluated. As a result of the Bayesian update, the reliability index increased to $\beta = 0.40$; however, the β value did not reach that in Step 1 ($\beta = 1.16$). In other words, the reliability of the boring inspection was not enough to decide whether to resume operation.

In Step 4 and Step 5, the effects of survival analysis are considered. In both tests, the assured load is smaller than the mean value of the applied external force S. Nevertheless, the reliability index β significantly increased and exceeded that in Step 1, which means that the decision to resume train operation based on the static loading and train running tests was valid from the perspective of reliability assessment.

6. Conclusions

This study assessed the reliability of residual bearing capacity of railway bridge foundation that damaged due to scouring. It was gradually increased by conducting various inspections and tests. The results quantitatively confirmed that after the reliability index β temporarily decreased because of scouring, it gradually increased following more information from tests and inspections conducted for the purpose of emergency restoration.

Typically, for disaster recovery management, it was essential to perform an engineering assessment with limited information. However, the number of experienced and well-trained engineers who can conduct this assessment is limited, and it is challenging to train engineers. Moreover, such engineering assessment and accountability are in a trade-off relationship. The concept of survival analysis provides useful information about quantitative changes in reliability, which can be useful for engineering assessment and can increase accountability.

The reliability index value β in this study changes based on various assumed conditions, although it is considered that the relative relationships of reliability obtained at each step are not significantly affected by the differences in assumption conditions.

In the future, introducing reliability-based safety assessments (as a reference for relative reliability while conducting qualitative engineering decisions as shown in this research), without relying on direct inspection methods for reliability, will allow engineers to accept and incorporate reliability methods.

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References

Kuroki, Y., Nishioka, H., Kumabe, K. and Koda, M. 2018. Reinforcement of Dameged Bridge Pier by Scouring Using Steel Pipe Piles. In *Proceedings of the First International Conference on Press-in Engineering 2018*, Kochi, Japan, September 19–20, 2018. IPA, Tokyo, pp. 549–554.

Schweckendiek, T. 2011. REASSESSING RELIABILITY BASED ON SURVIVED LOADS. *Coastal Engineering Proceedings*, 1(32): structures.23.

Schweckendiek, T., Vrouwenvelder, A.C.W.M. and Calle, E.O.F. 2014. Updating piping reliability with field performance observations. *Structural Safety*, 47(1): 13-23.