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PROPOSAL OF RESTORABILITY EVALUATION METHOD FOR RAILWAY STRUCTURES USING THE RECOVERY TIME AFTER AN EARTHQUAKE

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ABSTRACT: We propose a method to evaluate the restorability of railway structures. In the proposed method, all earthquake motions expected within a structure's design service life are used as the design earthquake motions. In addition, the recovery time after an earthquake, which is directly related to early recovery, is used as the verification index. We also propose a more practical method of representing structural conditions that correspond to the same recovery time using a nomogram by performing calculations under various conditions in advance. The proposed method allows us to design structures that can be restored more easily, following the same procedure as conventional seismic design, and it is expected to shorten the recovery time after an earthquake.

Keywords: *Seismic design, Restorability evaluation method, Recovery time after an earthquake, Railway structure*

1. INTRODUCTION

In addition to ensuring safety, infrastructure facilities developed as foundational structures for industrial and residential areas are required to ensure restorability during earthquakes. For example, railway structures need to "remain in a condition that allows functional restoration in a short period of time by limiting damage to a range defined by the difficulty of structural repair in response to expected seismic action" [1]. One approach to confirming the restorability of these structures is to verify that the recovery period and expenses are within a reasonable range when subjected to multiple seismic motions expected during their design service life, considering both initial construction costs and earthquake-related costs[2]. Various facilities have undergone examinations that consider the total cost[3)–5], and there are cases where this has been introduced into seismic design[6]. We previously proposed a design method for minimizing the total cost of railway RC piers[7].

Following the trends described above, the restorability of railway structures after seismic damage is, in principle, verified according to the concept[1]. On the other hand, there have been moderate earthquakes in recent years, such as the 2018 Northern Osaka Earthquake, the 2021 Earthquake off the

Coast of Fukushima Prefecture, and the Northwestern Chiba Earthquake. Although structural damage in these earthquakes was limited, determining the extent of damage and undertaking post-earthquake restoration work took time. Issues regarding the early resumption of operations and post-earthquake restoration have been highlighted[8]. Methods to address such issues may include cost-based restorability verification and the explicit calculation of the recovery time after an earthquake, which can be used as an indicator for structural design. From this perspective, we previously calculated the relationship between the damage level caused by the earthquake and the recovery time required for various railway structures. We then prepared a database[9], which makes it relatively easy to calculate the recovery time for each structure after an earthquake. However, implementing these methods requires specialized design techniques and knowledge, as well as relevant information such as the probability of earthquakes and the concept of loss costs. Analytical techniques for large-scale numerical calculations are also necessary. Therefore, similar to when calculating the total cost of a structure, it is expected that implementing this method in practice will be difficult.

In this paper, we propose a method for verifying the restorability of railway structures. In Section 2, we propose a verification method for railway structure restorability in which the recovery time is used as the verification index. We propose a basic procedure and present a display method called the Restorability Verification Nomogram (RVN), hereafter abbreviated as RVN. This RVN enables implementation in practical designs. In Section 3, we perform trial calculations to verify the restorability of reinforced concrete (RC) rigid-frame viaducts. In Section 4, we evaluate and validate RVN for the structure that was subject to trial calculations in Section 3.

2. PROPOSAL OF RESTORABILITY VERIFICATION METHOD WITH RECOVERY TIME AS A VERIFICATION INDEX

2.1 Proposal of restorability verification method

First, we propose a method for verifying the restorability of railway structures using recovery time after an earthquake as the verification index. Figure 1 shows the proposed verification procedure. The general flow process involves setting the required performance and design earthquake motion, calculating the structural response and verifying its performance. This process is equivalent to the seismic design procedure of normal railway structures[1]. Meanwhile, the design method proposed here has several features.

The “recovery time after an earthquake” is set as the required performance of the structure. This directly addresses the issue of recovery time after an earthquake, which has become a serious concern

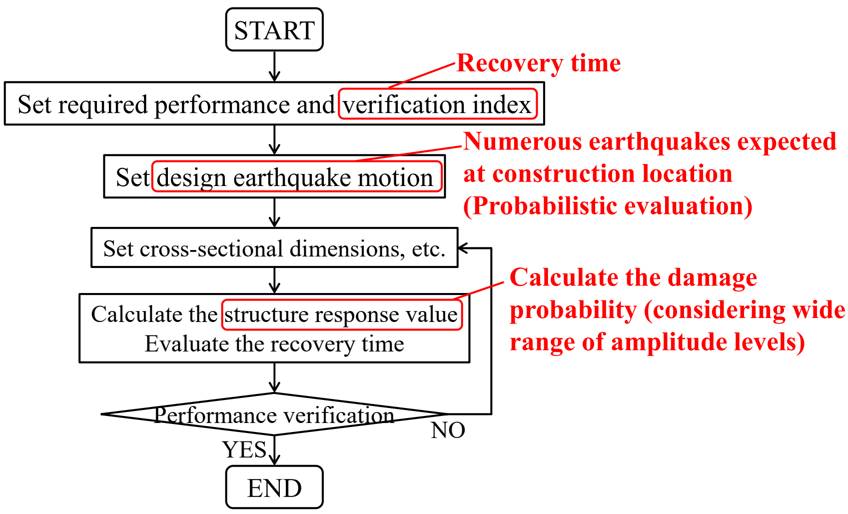


Fig. 1 Proposed restorability verification procedure

in recent medium- to large-scale earthquakes. Various earthquake motions are expected to act on structures in service at this time, resulting in damage and restoration work. The verification index to verify the recovery time is set as the expected recovery time for a group of earthquake motions, where the design earthquake motion is set as multiple earthquake motions acting on the structure at the target location.

To correspond to the above-mentioned verification index, the design earthquake motion must be set as “multiple earthquake motions with a wide range of characteristics expected at the construction location.” These seismic actions are represented by a set of waveforms, and its occurrence probabilities[10), 11)] are represented by the results of probabilistic earthquake risk analysis[12), 13)].

The method for calculating the structural response is based on conventional seismic design practices. It should be noted that the current seismic design of railway structures aims to accurately evaluate the response to L2 earthquake motion. The structures are modeled to respond relatively safely to earthquake motions with smaller amplitudes than an L2 earthquake, such as the L1 earthquake and other earthquakes. However, the restorability verification method proposed in this paper requires calculating the appropriate earthquake response values for small- and medium-sized earthquakes. Therefore, it can effectively adopt a structural modeling method and response value calculation method that considers such aspects[14)].

Finally, the recovery time of the structure is evaluated. This requires setting a recovery time that corresponds to the response value of the structure. However, the time required for recovery can naturally vary greatly depending on the part of the structure that is damaged and the degree of damage. Recovery is known to vary greatly depending on circumstances, such as the structural type and surrounding environment. Therefore, the recovery time must be appropriately evaluated in accordance with the earthquake response value and the situation at the location. We previously conducted a basic examination of the relationship between earthquake response value and recovery time under standard railway structure conditions[9)]. The results of this examination are used in the following calculations.

The above procedure enables us to calculate the expected recovery time for a group of earthquake motions. In this procedure, the design earthquake motion is set as multiple earthquake motions acting on the structure at the target location. We plan to verify the performance by determining if it meets the required recovery time. Meanwhile, performance verification is conducted using the following equation, which is based on the limit state design method—the standard design method for railway structures.

$$\gamma_{\mathrm{i}} \cdot \frac{I_{\mathrm{RD}}}{I_{\mathrm{LD}}} \leq 1.0 \quad (1)$$

The parameters are defined as follows: I_{RD} denotes the design structural response, representing the expected recovery time; I_{LD} denotes the design limit value, representing the required recovery time; and γ_{i} denotes the structural factor, which is set to 1.0 in this study.

2.2 Restorability verification nomogram (RVN)

The proposed method requires a large amount of work to set the design earthquake motion, calculate the response value, and verify the performance. Consequently, implementing this method for all structures in actual designs is difficult. Therefore, we propose a more practical method.

To verify practical restorability, it is necessary to simplify each stage of work, and the strength demand spectra[1)] used in the seismic design of railway structures can then be a useful reference here. This term involves an advanced calculation of the response ductility factor μ (ratio of maximum response displacement δ_{max} to yield displacement of the structure δ_{y}) under a wide range of structure conditions (equivalent natural period T_{eq} and yield seismic coefficient k_{hy}) for a certain design earthquake motion and displaying the T_{eq} and k_{hy} that have the same response ductility factor as a spectrum, as indicated in Fig. 2. These terms make it easy to calculate δ_{max} from only the vibration characteristics (T_{eq}, k_{hy}) of the target structure, and δ_{max} and limit displacement are compared to conduct the performance verification of the structure.

Therefore, we propose a method to evaluate the recovery time under a wide range of conditions in advance, similar to the strength demand spectra. We display this as a restorability verification nomogram

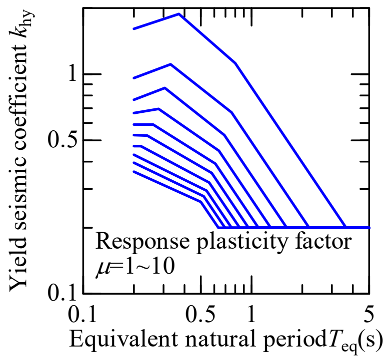


Fig. 2 An example of yield seismic coefficient demand spectrum

(RVN). Figure 3 presents the calculation procedure for RVN. An overview of each step is given below.

Step 1: Set the target location. Then, evaluate the design earthquake motion at the location. This involves considering multiple earthquake motions with a wide range of characteristics expected at the construction location. This is expressed as a group of earthquake motions and their respective probabilities.

Step 2: Calculate the structural response against the design earthquake motion. First, build a group of structure models with different yield seismic coefficients k_{hy} for conditions with T_{eq} and μ. Conduct a dynamic analysis on this structure by inputting the earthquake motion waveforms at the target point. Then, calculate the response ductility factor and occurrence probability of the degree of damage for each structure.

Step 3: Evaluate the recovery time corresponding to the damage obtained in Step 2. Then, multiply it by the occurrence probability to evaluate the expected recovery time.

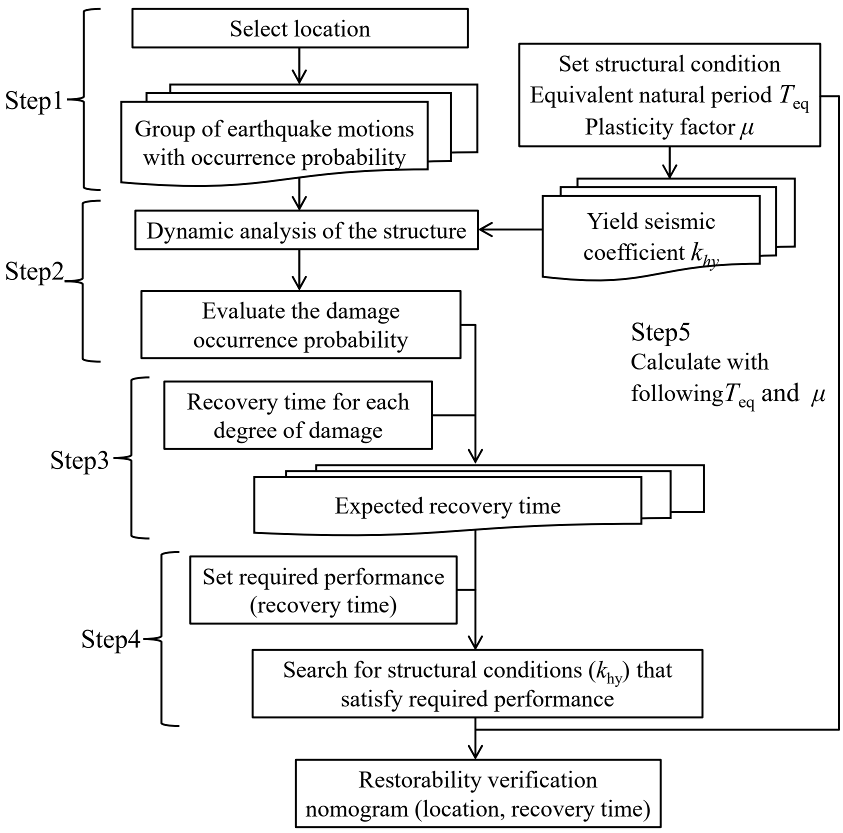


Fig. 3 Nomogram calculation procedure for restorability verification

Step 4: Set the required performance of the structure (target recovery time). Then, determine the structure that satisfies the required performance based on the relationship of the expected recovery time obtained in Step 3. The structure is a combination of T_{eq}, μ, k_{hy}.

Step 5: Repeat Steps 2–4 by varying the T_{eq} and μ. Using these results, connect the conditions that result in the same recovery time. This will display the combination of the structure's vibration characteristics that satisfies a certain recovery time via a nomogram.

This procedure displays the same dimensions corresponding to the strength demand spectra for a location and recovery time. The calculation conditions for creating the above RVN are compared with those based on the fundamental method proposed in the previous section. In addition, research has confirmed that appropriate earthquake response values and damage occurrence probabilities can be calculated for railway bridges and viaducts, even if the entire structure is replaced with an equivalent single-degree-of-freedom (SDOF) system[15)]. Thus, an analysis model can be used to obtain equivalent results for both. Moreover, RVN displays the characteristics of the structure based on the recovery time. Therefore, it can be used for any required performance and recovery time. The proposed RVN uses the same seismic action as the fundamental method described in Section 2.1. The same results are obtained for the structural response value and recovery time. This suggests that the work required for verification has been considerably reduced and that an appropriate restorability verification has been achieved.

In Step 2, the "recovery time according to each earthquake response value of the structure" needs to be calculated. Since this varies considerably depending on the damaged part and the surrounding environment, multiple nomograms need to be prepared as required. Further study is needed on how to create and display a simple nomogram that considers this aspect appropriately. In this paper, however, we plan to estimate a nomogram using the relationship between earthquake response values and recovery time under standard conditions[9)].

2.3 Design procedure using restorability verification nomogram (RVN)

RVN simplifies the determination of the seismic yield coefficient demand according to various conditions, such as the earthquake seismicity of the construction location, the vibration characteristics of structure, deformation performance, damaged areas, ease of restoration, and required performance. We summarize the restorability verification procedure for a structure using RVN. Figure 4 shows the specific flow process. The differences from the basic restorability verification method proposed in Section 2.1 (Fig. 1) are listed below.

・In "design earthquake motion setting," the basic method uses a group of earthquake motions with occurrence probabilities for each region. However, in our examination, we select RVN based on various conditions.

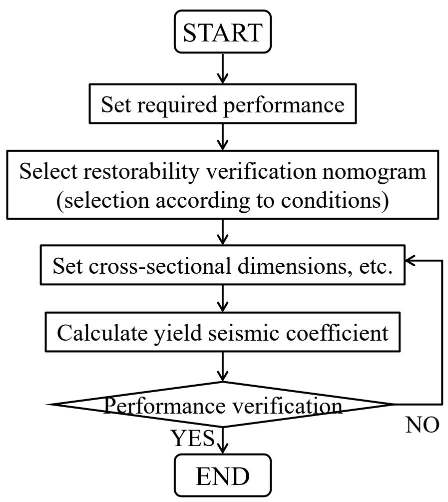


Fig. 4 Restorability verification procedure for structures using RVN

・In the “structure response value calculation and recovery time evaluation,” the basic method uses each waveform to evaluate the response value, damage level, and recovery time. However, in our examination, we calculate the structure’s yield seismic coefficient k_{hy} is from the results of the push-over analysis.
・In the “performance verification,” the basic method uses Eq. (1) to verify the recovery time. However, our study confirmed that k_{hy} of the target structure is equal to or greater than the required yield seismic coefficient calculated by RVN.

As previously described, an advanced preparation of RVN based on various conditions enables verification using recovery time as the verification index because its function is similar to performance verification using the strength demand spectra. Therefore, this method is considered a design procedure that can be applied to practical designs. The validity of these results is confirmed in Section 4.

3. RESTORABILITY VERIFICATION OF STRUCTURES BASED ON THE PROPOSED METHOD

3.1 Setting required performance and verification index

We verify the effectiveness of the proposed method by applying the basic procedure of the restorability verification method to an actual railway structure. The ground conditions shown in Fig. 5 are used as prerequisites for the calculations. The target structure is a rigid-frame viaduct, which has a height of 12.2 m from the ground to the track. The outcome of this method varies depending on the seismicity of the assumed area. Therefore, a construction location needs to be set. For this study, the Sendai area was selected as the location. We designed a cross-section to satisfy the required recovery time at this location.

The proposed method set the “expected recovery time after an earthquake” as the required performance of the structure. In this case, the expected recovery time is set to five days. Although there is room for debate on how to set this value, the average recovery time is five days according to trial calculations conducted in major regions across the country for multiple structures designed according to current railway standards (rigid viaducts with pile foundations, where the upper structure yields first). Therefore, we adopted this value in our study, considering the perspective of code calibration. This recovery time of five days corresponds to the design limit value I_{LD} in Eq. (1).

3.2 Setting the design earthquake motion

In the proposed method, the earthquake occurrence probability and design earthquake motion are set based on the construction location. For this trial calculation, we conducted a probabilistic earthquake hazard analysis in the Sendai area, which was set as the location. The return period for the calculation

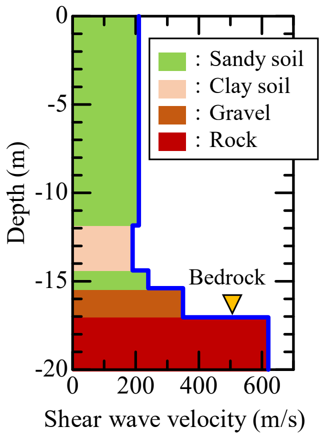


Fig. 5 Ground condition

is set to 100 years, which corresponds to the design service life[1] of the structure. The specific implementation procedure of the earthquake hazard analysis and the information used are based on reference[13], which includes the calculation method for the earthquake motion waveform group described later. Figure 6 shows the final evaluation results of the earthquake occurrence probability.

This result was used as the basis for synthesizing the group of earthquake motions by occurrence probability. For this examination, we divided the amplitude into 15 levels with 100 Gal increments from 100 to 1,500 Gal ("Gal" refers to cm/s^2). Twenty waves were evaluated for each amplitude level for a total of 300 waves. Figure 7 presents an example of the final calculated waveform. Naturally, the magnitude M_w and epicenter distance R assumed for each earthquake motion waveform differ, affecting not only the amplitude but also the time and frequency characteristics. A group of earthquake motion waveforms is set as the design earthquake motion.

3.3 Structure response value calculation and recovery time evaluation

The dimensions and sectional reinforcement of the rigid-frame viaduct were determined based on the various conditions at the construction site. The cross-section was designed to satisfy the verification of restorability using our proposed method, as well as normal structural safety. Finally, we set the structure dimensions and section reinforcement shown in Fig. 8. Note that only the columns and piles are shown for the cross-sectional reinforcement for subsequent discussions. We developed a model to calculate the structural response to earthquake motions. The model is created using two-dimensional beam and spring elements in accordance with various design standards for railway structures[1]. The elastic and nonlinear characteristics of each element are modeled in accordance with railway standards. Figure 9 shows the results of a push-over analysis perpendicular to the track. This analysis reveals the structure's equivalent natural period is T_{eq} = 1.14 s and its yield seismic intensity is k_{hy} = 0.33. We note that points Y, M, and N in this figure are damage control points used to evaluate the number of days required for structural restoration.

A nonlinear dynamic analysis that uses the detailed model of the structure can be conducted to calculate the response value. However, we replaced this model with an equivalent SDOF system,

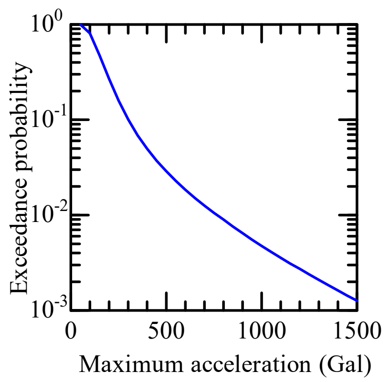
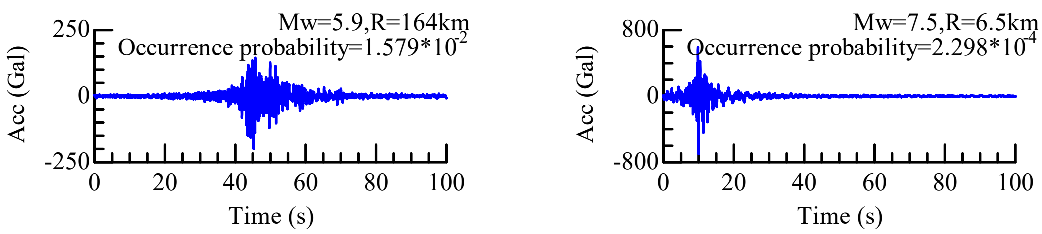


Fig. 6 Evaluation results of earthquake occurrence probability (Sendai area)



(a) Maximum acceleration of 200 Gal (b) Maximum acceleration of 700 Gal

Fig. 7 Calculation results of the group of earthquake motions with occurrence probability (Sendai area) considering the number of seismic waves used[1), 14), 15)]. We conducted a dynamic analysis by comprehensively inputting all 300 earthquake motion waveforms calculated in the previous section into the analysis model of this structure. Then, we calculated the response value for each waveform. Figure 10 shows the results of organizing the relationship between the response ductility factor of the structure and exceedance probability from the maximum response displacement of each waveform. This figure shows the control points (μ_y, μ_m) of each form of damage obtained by the push-over analysis of the target structure. However, in our examination of structures and earthquake motions, there was no response that exceeded μ_n, which corresponds to the collapse of the structure.

We calculated the recovery time of the structure based on the relationship with the standard recovery time corresponding to the structure type and degree of damage that we described in a previous study[9)].

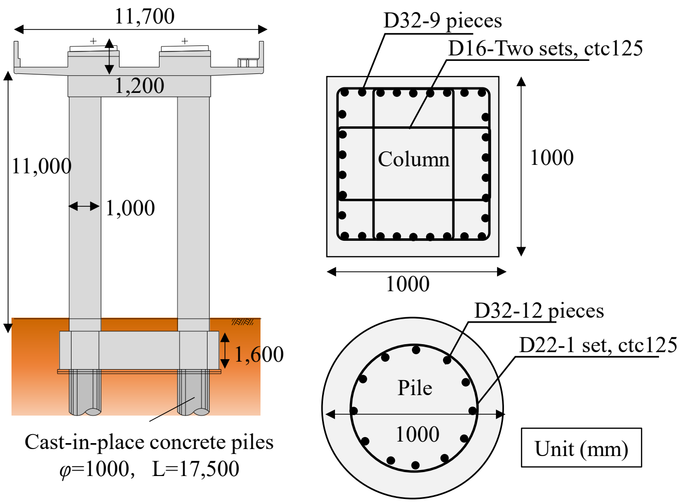


Fig. 8 Set structure dimensions and reinforcement of columns and pile sections

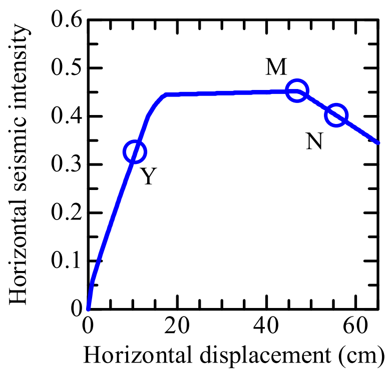


Fig. 9 Load-displacement relationship of entire structure

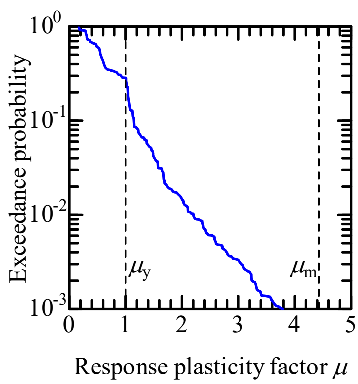


Fig. 10 Damage occurrence probability of structure

Table 1 Relationship between degree of damage and recovery time

Damage level	Response ductility factor μ	Recovery time (days)
1	$0 \leqq \mu < \mu_y$	1
2	$\mu_y \leqq \mu < \mu_m$	8
3	$\mu_m \leqq \mu < \mu_n$	23
4	$\mu_n \leqq \mu$	28

As shown in Table 1, the maximum response displacement of the structure and corresponding number of days to recovery were set to the damage level for the rigid-frame viaduct. The details of the calculation conditions and method for recovery time are based on reference[9]. The damage level of the structure is the same as the definition of seismic design for railway structures[1]. We assume ideal conditions for the surrounding environment of the structure, including sufficient workspace and the ability to bring materials and equipment in and from the side road. The expected recovery time of the structure is calculated by combining the relationship between the structural response and recovery time with the occurrence probability of each degree of damage shown in Fig. 10. The results showed that the expected recovery time of the target structure was 3.0 days. This corresponds to the design response value I_{RD} in Eq. (1).

3.4 Performance verification of the structure

We verified the restorability of the structure using Eq. (1). Assuming the structural factor $\gamma_I = 1.0$, using the expected required performance and recovery time from the study in the previous section, the value is obtained by the following equation.

$$\gamma_i \cdot I_{RD}/I_{LD} = 1.0 \cdot 3.0/5 = 0.60 \leq 1.0 \quad (2)$$

This indicates that the structure shown in Fig. 8 satisfies the performance requirements. However, if Eq. (2) were to fail to meet the performance requirements, then the structural cross-section would be reviewed, as shown in Fig. 1. The recovery time would then be calculated using the same procedure.

We confirmed that using the proposed method to evaluate the design earthquake motion, calculate the response value, and conduct the performance verification enabled us to design a structure that satisfied the required recovery time at the relevant location.

4. RESTORABILITY VERIFICATION OF STRUCTURES USING THE RESTORABILITY VERIFICATION NOMOGRAM (RVN)

4.1 Evaluation of the restorability verification nomogram (RVN)

We confirm the effectiveness of using the nomogram for the structure in this section. The target examination area is set as the Sendai area, and the target recovery time is set to “5 days.”

The equivalent natural period of the structure was set to T_{eq} = 0.5 s, and a response analysis was conducted under conditions where the M-point ductility factor (μ_m) and the yield seismic coefficient (k_{hy}) were both changed. Then, we used the same procedure as in the previous section to calculate the expected recovery time of each structure using. Figure 11 shows the results. It is now conceivable to use the N-point ductility ratio, which defines damage level 4, as a structural parameter for estimating recovery time. However, in designing railway structures, structural details are focused on ensuring safety against Level 2 (L2) seismic motions, which are the largest anticipated ground motions at a given site. In this study, the N-point ductility ratio is not included as a parameter since the damage level 4 will not

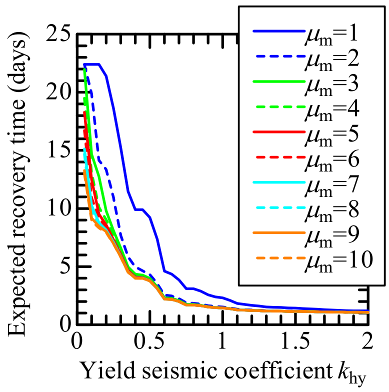


Fig. 11 Recovery time calculation results (T_{eq} = 0.5 s)

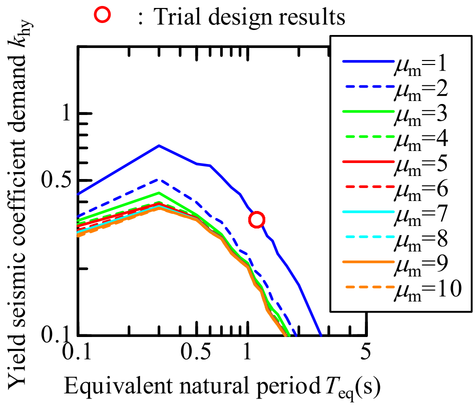


Fig. 12 Calculation results of RVN (Sendai area: recovery time is five days)

be reached under the design seismic motion. In the seismic design of railway structures, events with an extremely low probability exceeding the L2 level are usually addressed within the framework of "resilience against catastrophic events."

As shown in Fig. 11, the expected recovery time decreases as the k_{hy} of the structure increases. Furthermore, the recovery time shows low sensitivity to μm when the ductility factor μ_m of the structure is 2 or greater. Figure 10 shows that this can be attributed to the relatively small probability of a structure suffering major damage. In terms of the recovery time, information on the yield seismic coefficient becomes more important when μ exceeds 1. This figure can be used to easily calculate the k_{hy} of a structure with the target performance of a recovery time of five days. For example, if μ_m = 1, then a yield seismic coefficient k_{hy} approximately 0.6 satisfies the recovery time of five days.

A similar examination was conducted for various T_{eq} values. Figure 12 shows the relationship between T_{eq} and k_{hy} resulting in a recovery time of five days for each ductility factor μ_m. This is RVN proposed in Section 2.

As shown in Fig.12, RVN can be used to easily determine the combination of T_{eq}, k_{hy}, and μ_m of a structure that satisfies the required recovery time in the region (five days in this case). If the k_{hy} of a structure is equal to or greater than the vertical axis of the nomogram, then the expected recovery time of that structure will be five days or less. Therefore, the vertical axis of the nomogram is labeled "yield seismic coefficient demand" referring to the yield seismic coefficient required to achieve a recovery time of a certain length or less. In addition, RVN calculated in this examination showed that the demand of the yield seismic coefficient is high for structures with μ_m = 1. However, the demand is similar for structures with $\mu_m \geq 2$. Figure 11 shows that differences in damage and deformation performance do not significantly affect the recovery time of structures undergoing large deformation.

Furthermore, Fig. 12 shows RVN, which plots the trial design conditions of the structure from Section 3 (T_{eq} = 1.14 s, k_{hy} = 0.33) as a red circle. The M-point ductility factor of the structure is μ_m =

4.43, However, according to the nomogram, the yield seismic coefficient of the structure is slightly larger than the yield seismic coefficient demand. Therefore, RVN can be used to appropriately verify the performance design of the structure section. It can be said that the proposed nomogram can be used in the general design procedure when a recovery time is considered as the verification index.

4.2 Changes in the restorability verification nomogram (RVN) when conditions change

In the previous section, we evaluated RVN when the recovery time in the Sendai region was set to five days. We performed trial calculations to understand the sensitivity of RVN when these conditions change.

4.2.1 Changes in the evaluation area

We evaluated three areas with different earthquake seismicity values (Tokyo, Sendai, Sapporo) to understand the effect of changes in earthquake occurrence probability on the final nomogram. Figure 13 shows the evaluation results of earthquake occurrence probability in each area, where in the three areas targeted in our study, the earthquake occurrence probability gradually decreases in the descending order of Tokyo, Sendai, and Sapporo.

We calculated RVN for these three areas. The recovery time was set to five days in all cases, and all other calculation conditions were the same as in the previous section. In other words, calculations were conducted in three regions, with the only difference being the conditions of the group of earthquake motions with an occurrence probability that was input to the structure. Figure 14 reveals the final RVN. This figure shows only the results when the ductility factor of the structure is $\mu_m = 2$.

We can confirm from this figure that the yield seismic coefficient demand k_{hy} gradually decreased in the descending order of Tokyo, Sendai, and Sapporo when T_{eq} is equivalent. This is a physically natural result of the higher seismicity of the region resulting in a higher probability of damage to a structure, resulting in the higher strength of the structure being required for maintaining the same

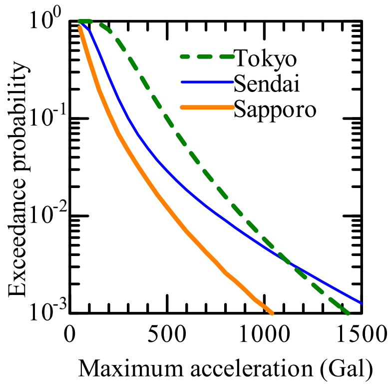


Fig. 13 Changes in earthquake occurrence probability by region

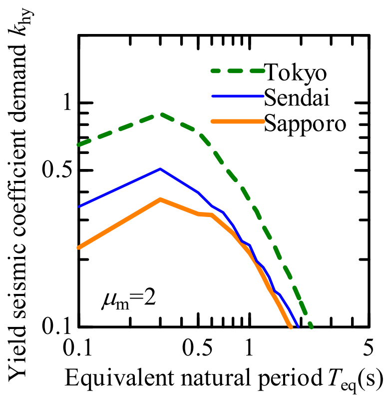


Fig. 14 Changes in RVN by region (recovery time of five days)

recovery time.

It follows that utilizing the concept of regional factors is expected to allow setting simple earthquake motion by "standard nomogram × regional factor".

4.2.2 Cases where the required recovery time changes

Next, we determine the effect of changes in the recovery time required for structures on RVN. We conducted calculations under conditions where the recovery time of five days evaluated in Section 4.1 was changed to 2 days. All other conditions are the same as in the previous section.

Figure 15 depicts the obtained RVN ($\mu_m = 2$). Based on this figure, we can confirm that a shorter target recovery time requires a large yield seismic coefficient for the structure. Although this is a natural result, it suggests that structures with the same equivalent natural period and ductility factor can achieve improved restorability by improving the yield seismic coefficient. In addition, when RVN under the condition of a structure's ductility factor $\mu_m \geq 2$ is almost identical as indicated in the previous section, we can confirm that the restorability of the structure can be effectively improved by improving the yield seismic coefficient rather than improving the deformation performance.

The tendency of the yield seismic coefficient demand k_{hy} changing in all natural periods with changes in the number of days to recovery is similar to the change in the earthquake seismicity for each region conducted in the previous section. Therefore, organizing the number of days to recovery considering the correction factor can achieve a simplified evaluation of "standard nomogram × correction factor according to number of days to recovery."

5. CONCLUSION

In this paper, we proposed a method for verifying the restorability of railway structures that uses the recovery time after an earthquake as the verification index. The results of our study were as follows:

- The proposed method uses "multiple earthquake motions with a wide range of assumed characteristics during the design service life" as the design earthquake motion, and the "recovery time" as the verification index. Recovery time is directly related to the speed of restoration after an earthquake. This allows for the seismic design of structures that consider the issue of recovery time.
- A trial design of a rigid-frame viaduct was conducted using the proposed method. The results indicate that the method allows for the seismic design of structures with recovery time as a direct verification index. However, since multiple dynamic analyses and damage evaluations are required each time the specifications of the structure change, this method of restorability verification during seismic design requires a large amount of effort.
- A more practical design method was proposed by conducting calculations under various conditions in advance and displaying the structural conditions resulting in the same recovery time in a nomogram.

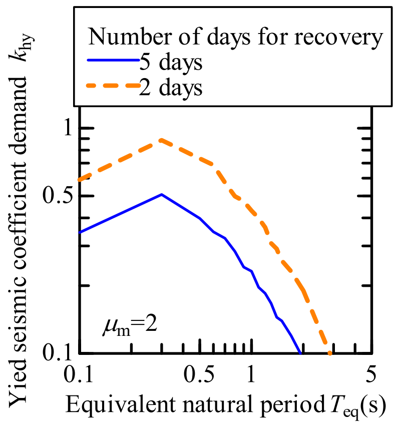


Fig. 15 Changes in RVN when recovery time changes

Additionally, trial calculations for the above-mentioned rigid-frame viaduct showed that the performance of structures can be verified using the restorability verification nomogram (RVN). This method can be used to design structures that can be easily restored using the same procedure as conventional seismic design.

・Trial calculations were conducted on RVN under conditions that changed the evaluation area and the required number of days for restoration. The results indicated that a concept similar to the regional factor used in conventional seismic design can be employed for dealing with a wide range of conditions using the procedure of "standard nomogram × correction factor corresponding to each condition."

The proposed method enables the design of new structures with enhanced restorability. Furthermore, identifying the parts and members of existing structures that require restoration in advance enables the implementation of targeted inspections and measures, ultimately shortening the recovery time after an earthquake. Additionally, evaluating existing structures based on their future service life can help determine the appropriate level of measures, set the same performance requirements, and optimize the priority of measures for special structures that require more time to recover.

However, it should be noted that this examination has limitations. First, it is based on a proposed method. Second, it uses trial calculations based on limited conditions, such as regions and structures. Moreover, recovery time for damaged structures can vary considerably depending on various conditions. While trial calculations in this examination consider the uncertainty and variance of earthquake occurrence and motion through probabilistic earthquake hazard analysis, they ignore the uncertainty and variance of structural response values and recovery time. Resolving these issues requires a more in-depth examination. This includes improving the evaluation of recovery time associated with structural damage, correcting RVN according to the structural characteristics, and considering structural responses uncertainty. Furthermore, standardizing the nomogram requires future evaluations under a wide range of conditions.

To validate the developed method, calculations of the earthquake hazard and structural response value and evaluation of the relationship between the damage degree and recovery time have been conducted individually in each field[9), 14)–16)]. Therefore, the evaluation of the expected recovery time accumulated by these elemental technologies has a certain degree of reliability; however, some lines have structures that were built many years ago, and therefore, verifying such lines and structures is possible. We plan to continue to work on these aspects in the future.

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