Quantitative Evaluation of Seismic Countermeasure Effects Focusing on Lost Transportation Volume of Railway Networks

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To improve railway resilience against earthquakes, we verify and apply a developed support system to evaluate the effects of seismic countermeasure, focusing on the lost transportation volume of the railway networks. The system calculates the recovery process of the transportation volume which decreases after an earthquake, using optimization calculation by which the lost transportation volume is to be minimized. This makes us evaluate quantitatively the effect of the countermeasures. In addition, a different recovery process can be relatively evaluated. In this study, first we evaluate the performance of the system based on past earthquakes. Then comprehensively compare the effects of several seismic countermeasures such as structural and operational countermeasures. This paper describes that the evaluated recovery process of the lost transportation volume with the developed system is useful to implement strategic seismic countermeasures.

Key words: resilience, support system, restorability database, railway network, lost transportation volume, seismic countermeasures

1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) is an earthquake of a scale which had never before been seen in modern-day Japan. The experience of this widespread and complex earthquake damage led to wide changes in Japanese policies on earthquake disaster prevention. More specifically, seismic performances have remained the same against general earthquakes, new requirements include flexibility in seismic performance to avoid catastrophic damage against earthquakes of unprecedented and unexpected scale. This is called resilience. The 2011 off the Pacific coast of Tohoku Earthquake also revealed the importance of being able to secure transportation volumes across transportation networks as a whole in the event of earthquakes which affect a wide area, focusing on the fact that railway lines form networks.

To improve the resilience of railway against earthquakes, both structural and operational countermeasures are fundamental. For example, there are structural countermeasures such as seismic reinforcement to increase the rigidity of structures and operational countermeasures such as train operation control to suspend trains when strong ground motion is predicted or observed. Nevertheless, the effects of various implemented countermeasure have not been evaluated from the perspective of the railway as a system composed of networks. Therefore, to enhance the resilience of railways against earthquakes, we propose a method to evaluate the effects of seismic countermeasure in a unified manner by focusing on minimizing the lost transportation volume on railway networks. We first examine the proposed method and then verify its applicability.

2. Overview and verification of an evaluation method

2.1 Outline of a system to support detour and restoration planning

Railway Technical Research Institute (RTRI) has developed a support system for detour and restoration planning for railways to derive the optimal restoration strategy for damaged sections and the optimal detour strategy in the event of a large-scale natural disaster, which affects the railway network over a wide area [1]. This system calculates the optimal human resources allocation required for restoration to minimize loss of transportation volume, and the optimal detour transportation strategy to minimize detour transportation costs. The lost transportation volume represents the total volume of the difference between the assumed transportation volume without a disaster, and transportation volume in the event of a disaster. Figure 1 shows the concept of lost transportation volume which is indicated by the gray area. In this study, we apply the developed support system to evaluate earthquake disaster recovery.

Figure 2 shows an overview of the input and output of the support system. The input is the time required for restoring damaged section, measured in days, shown as input A in Fig. 2, or the human resources, measured in persons*days, required for restoration operation, shown as input B in Fig. 2. The output obtained from the support system is the recovery process which is the result of the calculation to minimize loss of transportation volume based on a mathematical optimization method. In setting the input, the upper limit of human resources regarding both the section and the entire network should be given. The transportation volume is calculated section-by-section, which connects stations in the railway network. Each section technically has two different directional sections.
2.2 Verification of support system using past earthquake data

To verify the reliability of the support system in the event of an earthquake, we used data from the 2011 off the Pacific coast of Tohoku Earthquake. During this event, the railway network was affected by the earthquake for a long period of time. Using the actual days for restoration of the damaged section as the input A in Fig. 2, the support system makes a reproduction calculation of the freight transportation volume. The evaluation conditions in this study are as follows.

- The calculation target region affected by the earthquake is from the Kanto region, surrounding Metropolitan Tokyo, to Tohoku region in northeastern Japan.
- The calculation includes the period from March 1st, 2011, to May 31st, 2011.
- Freight transportation volume is calculated on a day-by-day basis. The volume of freight transported over multiple days is counted on the first date of shipment.
- The daily freight transportation volume in the reproduction calculation is based on the averaged actual freight transportation volume from March 1st to March 11th. The reproduction calculation does not take into consideration the overall decrease in demand caused by the earthquake.
- The freight transportation in the target region is calculated. If the origin station or the destination station is outside the target region, the first station or the last station within the target region is regarded as the origin station or the destination station.
- Freight stations in the Tokyo metropolitan area are integrated into a single station as a representative station.

Using the aforementioned evaluation conditions, we calculated the actual transportation volume between origin and destination stations within the target region. To reduce the calculation load, the top 10 pairs of origins and destinations (OD) with the largest transportation volume were selected for the calculation. The sections carrying these 10 OD-pairs were included in the analysis. The network comprises 16 directional sections and 8 stations, and the journey length for each pair is based on the actual route length, in kilometers.

Figure 3 shows the calculated freight transportation volume, relative to the actual 11-day average volume before the earthquake. In Fig. 3, the broken line indicates the calculated freight transportation volume based on restoration progress of the damaged routes after the 2011 off the Pacific coast of Tohoku Earthquake and the solid line is the actual volume. The rapid decrease in the volume just after the main shock is distinct. After that, the recovery process of the volume due to the gradual restoration is found. The result of comparing the calculated and actual volume shows the reproduction of the schematic tendency of the transportation volume. It shows some differences due to causes such as shutdown of local businesses, a demand difference depending on the day of the week, occurrence of aftershocks, notably on April 7th, and long consecutive holidays. However, the overall result demonstrates a fair reproduction performance. Although it is a limited verification of the reproduction of the transportation volume, we confirm that the support system has a certain reliability in the calculation for the recovery process of the transportation volume.

2.3 Building and verification of restorability database for railway structures

One of the inputs for the support system are the human resources (persons*days) required for restoration operations indicated as input B in Fig. 2. To improve the reliability of the recovery process output of the transportation volume derived by the support system, it is necessary to input human resources as precisely as possible. Accordingly, it is effective to build a database of human resources required for restoration in the wake of different types of earthquake damage, in advance. RTRI therefore built a restorability database [2]. According to the database, the human resources, days, and costs required for restoration operation are evaluated from both a structural damage and restoration method perspective. So far, various methods have been proposed to evaluate the restorability and the business continuity of railway transportation in case of earthquakes. In many conventional methods, however, the days needed for restoration work have been statistically determined based on data from past earthquakes. Hence, we think that earthquake damage prediction such as site-dependent seismic motion evaluation and individual structural seismic response are not sufficient to evaluate restorability.

We therefore developed a method to evaluate the human re-
sources and restoration days required, according to the individual damaged structure obtained from damage prediction. To build the restorability database, structural types and members were categorized. In addition, the restorability database was built with reference to construction performance, inter alia. Concrete damage corresponding to a damage rank shown in the design standard for railway structures (seismic design) [3] was set for predicted damage to each structure.

Figure 4 shows an example of the evaluation of the railway extension restoration ratio, which divides restored railway extension by target railway extension, in case of the 1995 Southern Hyogo Prefecture Earthquake. As shown in Fig. 4, the results of the estimated extension restoration ratio with a length of about 20 km shows that calculated results generally coincided with actual results. Therefore, we think that we can evaluate the proper human resources required as input for the support system using this restorability database.

![Figure 4](image)

**Fig. 4 Verification result of the restorability database due to the actual earthquake**

**3. Evaluation of seismic countermeasure effects considering railway network**

Temporary decreases in transportation volume on a railway network may be due not only to structural damage, but also operational restrictions, as shown in Fig. 1. When restoration is completed, or a facility has been inspected the transportation volume gradually recovers as train operations resume. In this chapter, we quantitatively evaluate the effects of implementing structural countermeasures, introducing operational countermeasure, and strategic restoration using the support system for a hypothetical railway network and verify the applicability of the proposed method.

**3.1 Evaluation procedure and condition setting**

To evaluate the effects of seismic countermeasures using the support system, we first determined the input information of the railway lines such as stations and sections, ground condition, structural type, and number of trains, as shown in Fig. 2. In this study, the hypothetical railway network, shown in Fig. 5, was prepared for the examination of the support system. The typical properties of the structure were set hypothetically. Secondly, the earthquake ground motion and calculated structural damage rank were set. Then, the human resources (persons*days) required for restoration operation were set for each section. The human resources were obtained from the restorability database mentioned in Section 2.3. Finally, after performing the optimization calculation of human resource allocation with the support system, the effects of seismic countermeasure were evaluated relatively.

In this study, the ground condition with amplification characteristics of earthquake ground motion due to subsurface ground was set on the assumption that the virtual railway network was located in the Kanto Plain in Japan as shown in Fig. 5. The earthquake ground motion is calculated based on the anticipated Northern Tokyo Bay Earthquake (M 7.3), which is one of the earthquakes predicted to occur within the Tokyo metropolitan area. The earthquake ground motion is calculated using the seismic intensity prediction formula of the Earthquake Early Warning (EEW) from the Japan Meteorological Agency (JMA) with the consideration of the ground characteristics [4]. The spatial distribution of the calculated earthquake ground motion by JMA seismic intensity, is shown in Fig. 6. The calculated JMA seismic intensity is 6.5 or more between station AC and station A. The structural damage ranks for viaducts are calculated using the methods of [5] and [6]. The structural damage ranks for embankments are calculated using the methods [7]. The viaduct damage is ranked in 4 stages according to the response plasticity ratio, and the embankment damage is ranked in 3 stages according to the amount of settlement. The structural damage rank without seismic reinforcement is shown in Fig. 7. The damage rank of bridge and viaducts between station B and station AC is set from rank 1 to rank 3, and the damage rank of embankments between station AC and station C is set rank 1.

The restoration human resources as the input B in Fig. 2 were set for each section, and the recovery process of the transportation volume ratio for each seismic countermeasure was calculated. The effects of seismic countermeasure were evaluated by the relative comparison of the recovery processes.

![Figure 5](image)

**Fig. 5 Setting hypothetical railway network ([ ] represents the number of trains)**

![Figure 6](image)

**Fig. 6 Setting of earthquake ground motion with JMA seismic intensity**

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3.2 Examination of applicability to evaluate the effectiveness of structural countermeasures

In this section, we evaluate the effect of seismic reinforcement implementation. When there was no seismic reinforcement in the hypothetical earthquake, structural damage mainly occurred in the section between station B and station AC as shown in Fig. 7. In this study, the effect of seismic reinforcement is evaluated on the assumption that no damage occurs when seismic reinforcement is implemented. When seismic reinforcement has not been implemented, the input of the restoration human resources is set in the damaged section. On the other hand, when seismic reinforcement is implemented, the input does not need to be set, the same as if it were set to zero. For the assumed structural damage, human resources needed for restoration work were calculated using the restorability database described in Section 2.3. By comparing the calculation results of the recovery process with and without seismic reinforcement, we can quantitatively evaluate the effect of seismic reinforcement.

Table 1 shows the input of the restoration human resources, and Fig. 8 represents the calculation results of the recovery process of the transportation volume ratio. Table 1 also shows the cumulant lost transportation volume ratio evaluated from the calculation results shown in Fig. 8. The cumulant lost transportation volume ratio is defined as the integral value of the lost transportation volume ratio, which is subtracted transportation volume ratio from 1.0 between the occurrence of an earthquake to the day of recovery completion. According to Table 1, the cumulant lost transportation volume ratio is minimized when the section between station AC and station A is reinforced. In other words, from the viewpoint of minimization of the cumulant lost transportation volume ratio in the entire railway network, it is found that the seismic reinforcement between station AC and station A is the most effective in implementing seismic reinforcement. These results show that the support system can be used to quantitatively evaluate the effect of structural countermeasures such as the seismic reinforcement.

3.3 Examination applicability to evaluate the effectiveness of operational countermeasures

In this section, the effect of operational countermeasures is evaluated on the assumption that running trains are quickly suspended and derailment is prevented by introducing an earthquake early warning system [8]. An assumed section of the running-vehicle derailment is between the station AC and the station A because the strongest earthquake ground motion occurs in this section. The conditions for structural damage are the same as those in Section 3.2. If derailment does not occur, it is not necessary to deal with the derailed vehicle, so restoration operation can be started instantly. By taking into account the necessary human resources for dealing with this derailed vehicle, we calculate the recovery process for the presence or the absence of derailment as well as the presence or the absence of an earthquake early warning system. Figure 9 shows the calculated recovery process of transportation volume ratio. The human resources required for dealing with a derailed vehicle are assumed to be 1000 persons*day in this study to examine the adaptability of the support system. According to Fig. 9, since the introduction of earthquake early warning allows the restoration operation to be started immediately without delay, the transportation volume ratio recovers quickly on the second day. The cumulant lost transportation volume ratio decreases by approximately 8% from 3.50 to 3.23. These results demonstrate the applicability of the support system to quantitatively evaluate the effect of operational countermeasures such as introduction of earthquake early warning systems.
3.4 Examination of applicability to evaluate the effectiveness of strategic restoration

In this section, to examine strategic restoration, we quantitatively evaluate the effect of allocating human resources required for restoration operation of the damaged structures. The conditions for structural damage are the same as those in Section 3.2. Strategic restoration is examined by setting an upper limit of human resources allocated to the entire railway network and individual sections. With regard to the upper limit of resources for each section, a uniform allocation is set to be 500 persons/day for each section. Alternatively, an intensive allocation is set to be 1000 persons/day for a section from station AC to station A as a dominant section with large number of trains and passengers, and 250 persons/day for other sections. The upper limit of the total resources is set to be 1000 persons/day in the entire railway network. Figure 10 shows the recovery process of transportation volume ratio. As shown in Fig. 10, the recovery is faster with uniform allocation until the third day after the occurrence of earthquake. On the other hand, after the 14th day, the recovery is faster with strategic allocation. The cumulant lost transportation volume ratios of the uniform allocation and strategic allocation are 4.18 and 3.91, respectively. Therefore, the cumulant lost transportation volume ratio is smaller for the strategic allocation than for the uniform allocation. These results demonstrate that it is possible to obtain quantitative information for making decisions about allocation of human resources for restoration operation. With regard to planning restoration of damaged structures, it was found that the support system can quantitatively evaluate the effect of concentrating restoration resources on important sections which usually carry a large number of trains and passengers.

3.5 Unified evaluation of each seismic countermeasure effects

In sections 3.2 to 3.4, we quantitatively described the recovery processes of the transportation volume ratio by the structural countermeasure such as seismic reinforcement implementation, operational countermeasures such as introducing earthquake early warning systems, and strategic restoration such as optimally allocating human resources after earthquakes. These recovery processes are calculated based on the unified criterion to minimize the cumulant lost transportation volume of the railway network by setting the input of the human resources and the upper limit ones for each section. Therefore, the recovery process of the transportation volume ratio for each countermeasure can be plotted on the same figure, and the evaluation result can be shown using the same index such as the cumulant lost transportation volume ratio. Figure 11 shows the recovery processes as a unified evaluation result of structural countermeasures, the operational countermeasure, and strategic restoration. Figure 12 shows the value of cumulant lost transportation volume ratios respectively. While the upper limit of human resources with no countermeasures is set to be 1000 persons/day, the upper limit of uniform allocation of human resources is set to be 500 persons/day. Figure 11 and Fig. 12 show that the resources are insufficient in case of the uniform allocation of human resources. According to Fig. 12, the cumulant lost transportation volume ratio is reduced by 63% due to implementing seismic reinforcement from station AC to station A and by 8% by introducing an earthquake early warning system, when compared to no countermeasures being introduced at all. These results confirm that the effect of seismic reinforcement implementation is significant on lost transportation volume under the conditions set in this study. On the other hand, it was found that the lost transportation volume ratio increases by 19% when human resources cannot be invested for restoration operation sufficiently due to the lack of human resources.

Conventional evaluations of effects of seismic countermeasure have been conducted specifically for each type of countermeasure such as structural countermeasures, operational countermeasures, and strategic restoration. However, using the support system applied in this study, it is possible to carry out a unified evaluation, and it may be possible to apply it for decisions made about investments before earthquakes and regarding recovery after earthquakes.

4. Conclusions

After the 2011 off the Pacific coast of Tohoku Earthquake, the concept of resilience to avoid catastrophic structural damage and achieve flexible restoration has become common in Japan. To improve the resilience of railways against earthquakes, it is important to strike a balance between structural countermeasures such as seismic reinforcement implementation, operational countermeasures such as earthquake early warning systems, and strategic restoration such as optimal allocation of finite human resources after earthquakes. It is also important to maintain the transportation volume on
the entire railway network.

In this study, we confirmed the applicability of the developed support system by calculating the optimum allocation of human resources. The optimum human resources allocation required for restoration operations can minimize the lost transportation volume in the railway network until the restoration works have been completed. The calculation results of the recovery process of the transportation volume by the support system can be used for quantitative evaluations and comparative examinations. To improve the resilience of railways against earthquakes, the support system may therefore be applied for planning investments into seismic countermeasures before earthquakes and for evaluating restoration operation policies after earthquakes.

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