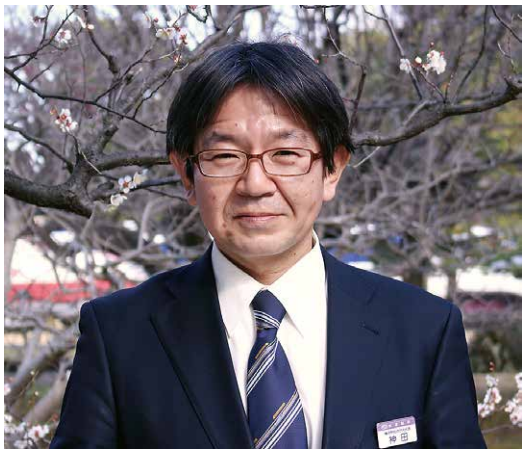


Improving Earthquake Resilience of Railway Structures



Dr. Masayuki Koda
(Director, Head of Structures Technology Division)

Ever since the 2011 Tohoku Earthquake off the Pacific coast efforts have been intensified to improve the resilience of railway structures on the Japanese mainland to earthquakes. Railway structures, such as bridges, elevated structures, tunnels, earth structures, and station facilities, vary widely in design. Careful consideration is required to ensure their structural integrity during earthquakes to prevent disastrous outcomes. This paper outlines measures developed by the Railway Technical Research Institute (Hereinafter referred to as RTRI.) to improve the quake resilience of railway structures, including pre-quake diagnosis and seismic reinforcement, early warning, quick estimation of quake motion and damage after the earthquake, and after-quake recovery support and early recovery techniques.

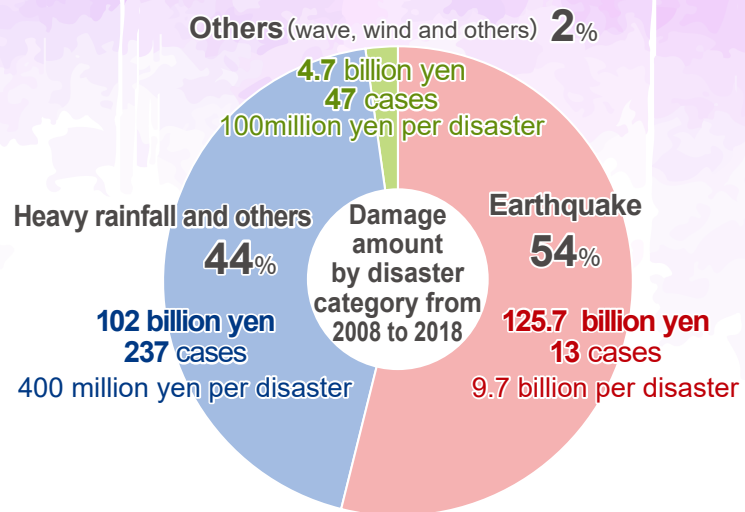
Ascent No. 12 March 2023

Editor-in-chief Kimitoshi Ashiya (Executive Vice President of RTRI)
Managing Editor Toru Miyauchi (Associate Director (International Affairs),
Research & Development Promotion Division of RTRI)
Publisher Railway Technical Research Institute
Address 2-8-38 Hikari-cho, Kokubunji-shi, Tokyo 185-8540, JAPAN
URL www.rtri.or.jp/eng
Contact us International Affairs, Railway Technical Research Institute
Mail Address International_development@rtri.or.jp
Copyright ©2023 Railway Technical Research Institute All rights reserved

Front cover : Examples of seismic reinforcement of railway facilities

Introduction

Over the past decade, railway facilities have suffered severe damages due to earthquakes such as the Tohoku Earthquake in 2011, Kumamoto Earthquake in 2016, Northern Osaka Earthquake in 2018 and Hokkaido Eastern Iburi Earthquake in 2018. Although railway disasters caused by earthquakes are fewer in number than those caused by rain, they account for more than half of the total damage to railway facilities in the past 10 years, i.e., 233.2 billion yen (*Cost of damages to railway facilities by natural disasters*). The severity of damage certainly influences recovery time. However, according to surveys by the Ministry of Land, Infrastructure, Transport and Tourism (hereafter referred to as MLIT), completely repairing railway embankments and slopes may require a few months, whereas repairing railway bridges and elevated tracks can take up to a few years¹⁾.



Cost of damages to railway facilities by natural disasters¹⁾

The 2011 Tohoku Earthquake off the Pacific coast was ocean trench quake with an unprecedented magnitude of 9.0. As piers of elevated structures had been reinforced to ensure the structural integrity of structures such as bridges in the aftermath of the Great Earthquake of Hanshin in 1995, most railway structures remained standing. However,

it still caused tremendous damage that was specific to large-scale earthquakes. Utility line poles and bridge piers were broken and damaged over vast areas, and additional damage was repeatedly caused by a series of aftershocks. The ground was liquefied in metropolitan areas, and the Tohoku coastal region sustained



Dr. Toru Miyauchi
Managing Editor
Associate Director (International Affairs),
Research & Development Promotion
Division

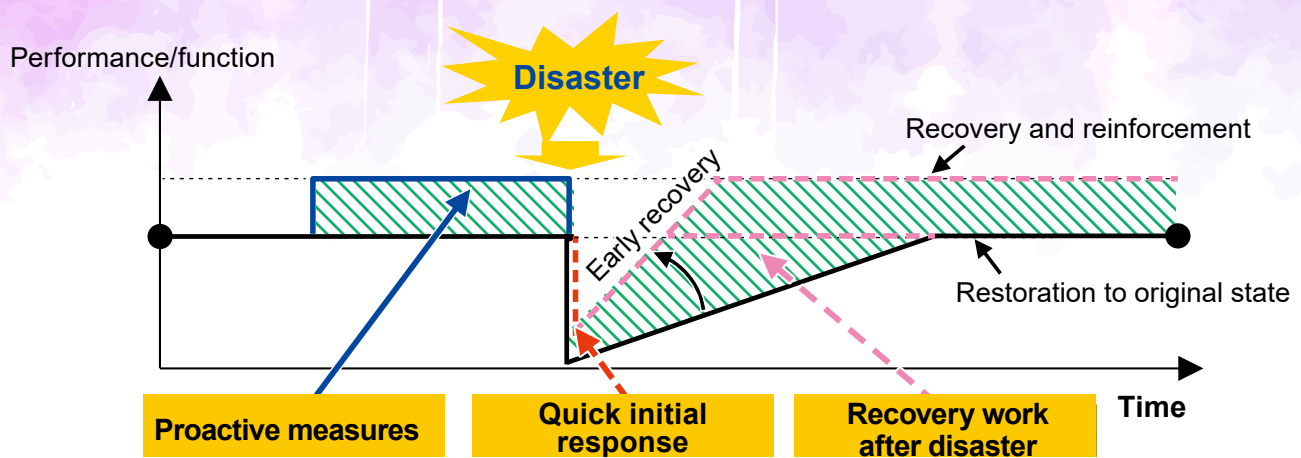
Message from Managing Editor Dr. Toru MIYAUCHI

Under the main theme “Technology to enhance the safety of railway structures during earthquakes”, this issue introduces technologies to support seismic safety, seismic assessment, and seismic strengthening of railway structures.

It also looks back at the World Congress on Railway Research held in June 2022 in Birmingham, UK (WCRR2022). I attended the conference as a member of the

Executive Committee, and I would like to report that it was a great success although held still under COVID-19 concerns. Presentations and discussions took place with 757 participants from 21 countries. I really appreciate the support and contributions to WCRR2022 by all the participants, sponsors, and organizers.

Your continued interest in Ascent is highly appreciated.



Performance and functions of structures before and after disaster²⁾

tremendous damage from the colossal tsunami. In the Kumamoto Earthquake, the main quake and repeating aftershocks impacted a wide stretch of land from the Kumamoto Plain to the Minami-Aso area²⁾.

Improving earthquake resilience

In the aftermath of a natural disaster, the railway structures require extensive work to recover their rapidly deteriorating performance and functions. In *Performance and functions of structures before and after disaster*²⁾, both “avoiding a catastrophic state (minimizing the red broken line)” and “early recovery and reinforcement of overall functions (increasing the slope of the pink broken line)” are defined as “earthquake resilience”. To improve the earthquake resilience of railway structures, the green-shaded area representing “proactive measures”, “quick initial response, and “recovery work” should be maximized.

Proactive measures include detecting vulnerable points in advance and upgrading structures to make them more quake-resistant, i.e., advance diagnosis and earthquake-proof reinforcement. A

quick initial response involves slowing down or stopping trains based on real-time quake information, and estimating the overall damage along an entire line as quickly as possible, i.e., early earthquake warning and instant estimation of quake motion and damage. These measures not only effectively mitigate damage but also aid in achieving seamless recovery in the aftermath of a disaster. The primary objective of recovery work is to determine the degree of structural damage sustained during the quake, and restart operations as quickly as possible if the damage is confirmed not to have any impact on the functioning of trains. In addition, the structures are immediately inspected to determine whether they only require reinforcement or need to be rebuilt or replaced. These measure constitute the early recovery techniques.

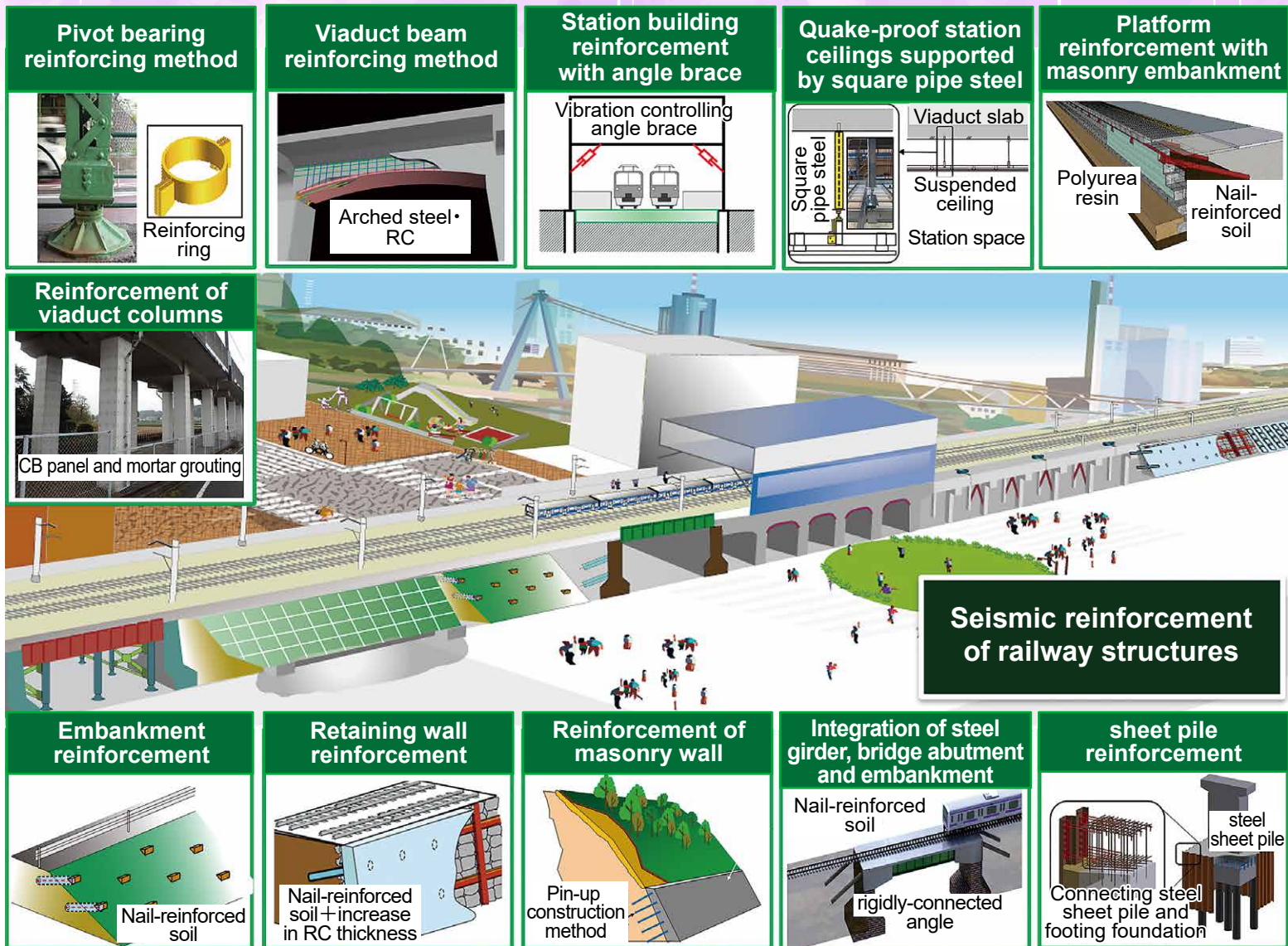
Proactive measures

(1) Advance diagnosis

Railways are linear structures composed of earth structures, bridges, elevated structures, and tunnels. In particular,

earth structures, including embankments, retaining walls, and slopes, were built earlier, and their total lengths are typically longer than those of other structures. Owing to the linear structure, railways lose their functions if any single part of the line is compromised. To address this problem, bridges, elevated structures, cut and covered tunnels, and stations of the conventional and Shinkansen lines in urban areas have been reinforced to improve their quake-proof performance after the devastation caused by the Great Hanshin Earthquake in 1995.

Meanwhile, earth structures that account for a major part of railway facilities must also be seismically reinforced. After the Great East Japan Earthquake in 2011, the MLIT developed the [Guide to Seismic Diagnosis for Railway Earth Structures \(Preliminary Diagnosis\)](#)³⁾ to aid authorities in identifying spots on earth structures that require inspection or reinforcement to ensure quake-proof performance. This guide was prepared as a recommendation to railway operators to implement the necessary quake-proof reinforcement of earth structures. RTRI also developed the



Examples of seismic reinforcement of railway facilities

Guide to Seismic Diagnosis for Railway Earth Structures (Detailed Analysis) ⁴⁾ to supplement MLIT's guide.

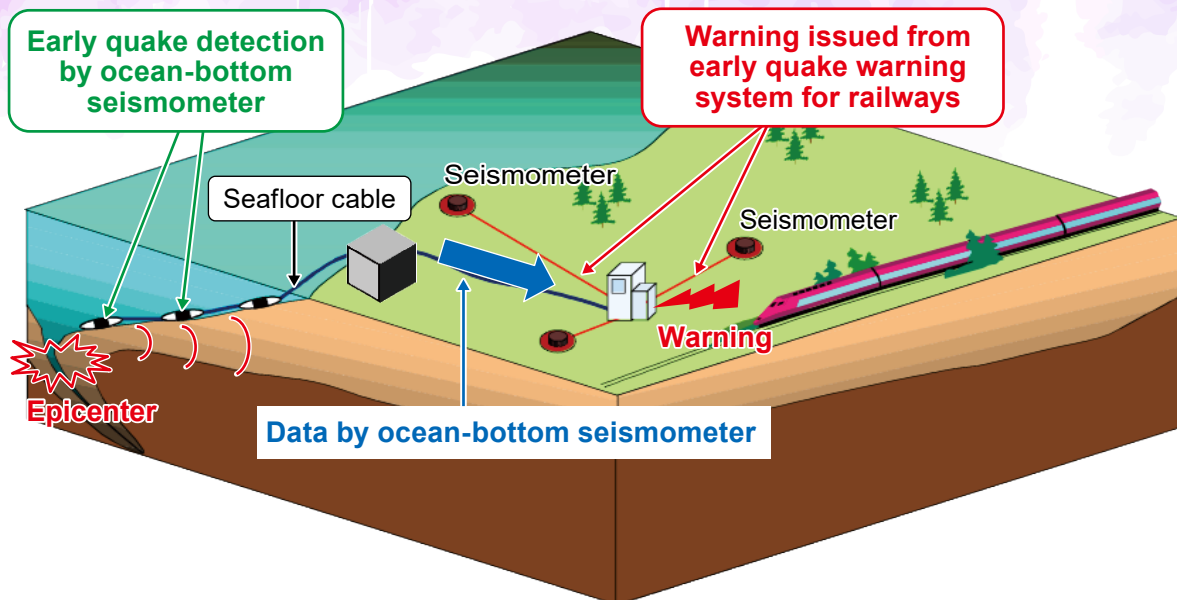
Furthermore, following the "Ministry Order on Seismic Reinforcement of Specified Railway Facilities" and partial revisions of "Enforcement Order for Building Standards Act" in 2013, RTRI has provided technical support for seismic diagnosis of railway

stations by developing the Seismic Diagnosis Guide for Steel-Framed Platform Roof ⁵⁾ and Design Materials for Quake-Proof Ceiling of Railway Stations ⁶⁾.

(2) Seismic Reinforcement Techniques

After the Great East Japan Earthquake, RTRI developed the "Technical Proposal for the

Recovery of Railways from Quake Damage" (*Examples of seismic reinforcement of railway facilities*) to support early recovery and reconstruction of railways and improvement of quake-proof performance of urban railways. *Examples of seismic reinforcement of railway facilities* shows the latest research outcomes published by the RTRI. The proposal recommends



Early Earthquake Warning based on ocean-bottom seismometer data⁸⁾

that the vulnerable points of urban railway facilities should be identified on priority and reformed to enhance their quake-proof performance.

Quick initial response

(1) Early earthquake warning technology

Early earthquake warning technology aids in achieving a quick initial response. The primary objective of using this technology is to control train operation before S-waves, i.e., major quake vibrations reach trackside areas. Specifically, in railway operation control, warnings based on P-waves (P-wave warning) and over-limit shaking (S-wave warning) are used.

An example of a technique used to achieve highly effective P-wave warnings is the epicenter distance estimation method that uses data from only one seismometer. This method was first introduced in the early

earthquake warning system for Shinkansen in 2004. At the time of its introduction, the method could calculate the distance of the epicenter within 2 s. With further development, the method was used to estimate epicenter distances even more accurately within 0.5 s during commercial operation in 2018⁷⁾.

In the meantime, a new S-wave warning method using ocean-bottom seismometers was developed. In the past, earthquake detection was difficult because only land seismometers were used to issue quake warnings for railways. Ocean-bottom seismometers improve quake detection because they can quickly detect ocean earthquakes, which constitute the majority of earthquakes in Japan. RTRI has been developing early quake warning techniques based on ocean-bottom seismometer data in cooperation with the National Research Institute for Earth Science and Disaster Prevention

(NIED) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). These two institutes have been developing and managing ocean-bottom quake-observation networks. The developed system screens warnings based on the properties of ocean-bottom seismometer data, a real-time data quality monitoring method, and an error prevention algorithm using data from several observation points. The system was introduced to Shinkansen in 2017 (*Early Earthquake Warning based on ocean-bottom seismometer data*)⁸⁾.

(2) Instant estimation technology for quake motion and damage

In the aftermath of the Northern Osaka Earthquake in 2018, train operations were delayed for an extremely long period. The extended delay was caused mainly because a large number of passengers on trains between stations had to be rescued while simultaneously confirming the safety



(a) Repaired after train operation restarted (repair)



(b) Repaired before train operation restarted (repair and position adjustment)

Diagnosis of Kyushu Shinkansen Viaduct damaged in Kumamoto Earthquake ¹⁰⁾

of railway facilities. To ensure that train operations can be resumed more quickly in such situations, a system has been developed to instantly estimate the degree of quake motion and damage.

In this system, shaking motions in trackside areas are estimated based on the observation data of K-NET by NIED and the ground database of RTRI. It also enables authorities to determine the damage levels of structures using a structural database that has been developed in advance and a damage-estimate nomogram. Since 2019, this system has been applied to commercial train operations and is known as damage information system for Earthquake on Railway (DISER) ⁹⁾.

Recovery work

(1) Recovery support

In the aftermath of a disaster, the RTRI immediately initiates support

measures to aid the recovery efforts of railway operators. During the Kumamoto Earthquake on April 14, 2016, pillars of RC rigid-frame elevated structures and bearings of Kyushu Shinkansen were damaged between the Shin-Tamana and Shin-Yatsushiro stations. Initially, concerns were raised that identifying damaged spots, which numbered well over 1000, and implementing a recovery plan would take an extremely long time. To speed up recovery, the severity of the damage was ranked, depending on whether the damage required repair prior to resuming operations, or whether it would interrupt operations. Subsequently, a sequential plan was implemented to resume low-speed operations before normal-speed operations for each section and damage rank (*Diagnosis of Kyushu Shinkansen Viaduct damaged in Kumamoto Earthquake*). Consequently, operations resumed between the Hakata and Kumamoto stations on April 23, 2016,

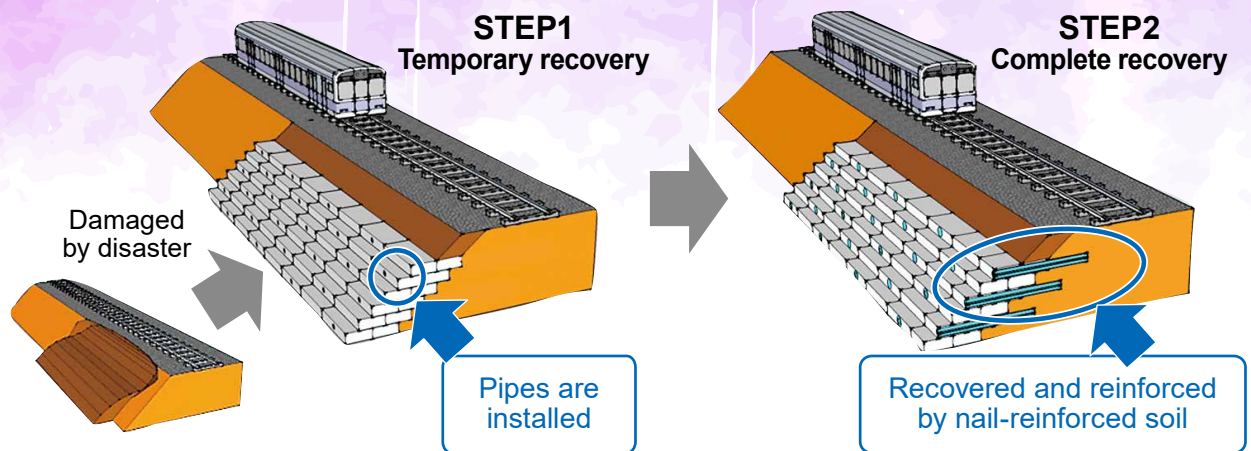
nine days after the earthquake, and across the entire Kyushu Shinkansen Line on April 27¹⁰⁾.

(2) Early recovery techniques

During recovery of damaged railway structures, resumption of train operation must be prioritized. Additional reinforcement work should, subsequently, be conducted in a phased manner. RTRI developed a technique to increase recovery speeds by temporarily repairing embankments using gabions. In this method, a damaged embankment is first repaired with gabions to ensure that operations can be resumed quickly; later, additional reinforcement work is undertaken (*Early recovery and reinforcement of damaged embankment using gabions and nail-reinforced soil*) ¹¹⁾.

Conclusions

To ensure the quake resilience of railway structures, several technologies and measures



Early recovery and reinforcement of damaged embankment using gabions and nail-reinforced soil ^{10), 11)}

need to be continually developed and improved. These include improving the accuracy of wide-area earthquake damage estimation, developing quake-proof reinforcement methods, reflecting the data of quake motion and damage obtained by instant estimation techniques on seismic designs and measures, and improving structural diagnosis technologies. RTRI will continue to share information with railway operators through events such as the Annual Meeting of the Center for Railway Earthquake Engineering Research, where a broad range of information on important research issues is shared, in addition to smaller meetings. Furthermore, it will continue to research and develop methods to improve “earthquake resilience” of railway structures and apply the outcomes to commercial operations.

References

- 1)MLIT: Policy Review for 2018 (Evaluation Report) – Disaster Prevention and Mitigation Measures for Railways, 2019.3(in Japanese) <<https://www.mlit.go.jp/common/001281980.pdf>>
- 2)Masayuki Koda: “Disaster Recovery Technology for Railway Structures”, *Journal of Japanese Geotechnical Society*, Vol.68, No.5, pp.5-8, 2020.5(in Japanese)
- 3)Supervised by MLIT, Edited by RTRI: *Guidance on Seismic Diagnosis for Railway Soil Structures (Preliminary Diagnosis)*, 2016(in Japanese)
- 4)RTRI Railway Technology Promotion Center: *Guidance on Seismic Diagnosis for Railway Soil Structures (Detailed Diagnosis)*, 2016(in Japanese)
- 5)RTRI Railway Technology Promotion Center: *Seismic Diagnosis Guide for Steel-Framed Platform Roof (3rd Edition)*, 2022(in Japanese)
- 6)RTRI Railway Technology Promotion Center: *Design Materials for Quake-Proof Ceiling of Railway Stations*, 2022(in Japanese)
- 7)Naoyasu Iwata, Shunroku Yamamoto, Masahiro Korenaga, Shunta Noda: “Stopping Trains Quickly and Safely by Early Earthquake Warning System”, *RRR*, Vol.73, No.3, pp.12-15, 2016(in Japanese)
- 8)Masahiro Korenaga, Shunroku Yamamoto, Makoto Aoi: “Using Ocean-Bottom Seismometer Data for Early Earthquake Warning”, *RRR*, Vol.76, No.3, pp.8-11, 2019(in Japanese)
- 9)Naoyasu Iwata, Kimitoshi Sakai, Shunroku Yamamoto, Yoshitaka Murono, Makoto Aoi: “Resuming Train Operation Quickly Using Damage Information System for Earthquake on Railway (DISER)”, *RRR*, Vol.77, No.2, pp.12-15, 2020(in Japanese)
- 10)Masayuki Koda: “Disaster Countermeasures and Early Recovery for Railway Structures”, *Abstracts of the 30th RTRI Conference*, pp.22-28, 2017.11(in Japanese)
- 11)Susumu Nakajima, Taketo Sato: “Method of Early Recovery and Reinforcement for Damaged Railway Embankment”, Vol.35, No.1, pp.47-52, 2021(in Japanese)