Toward Railway Innovation

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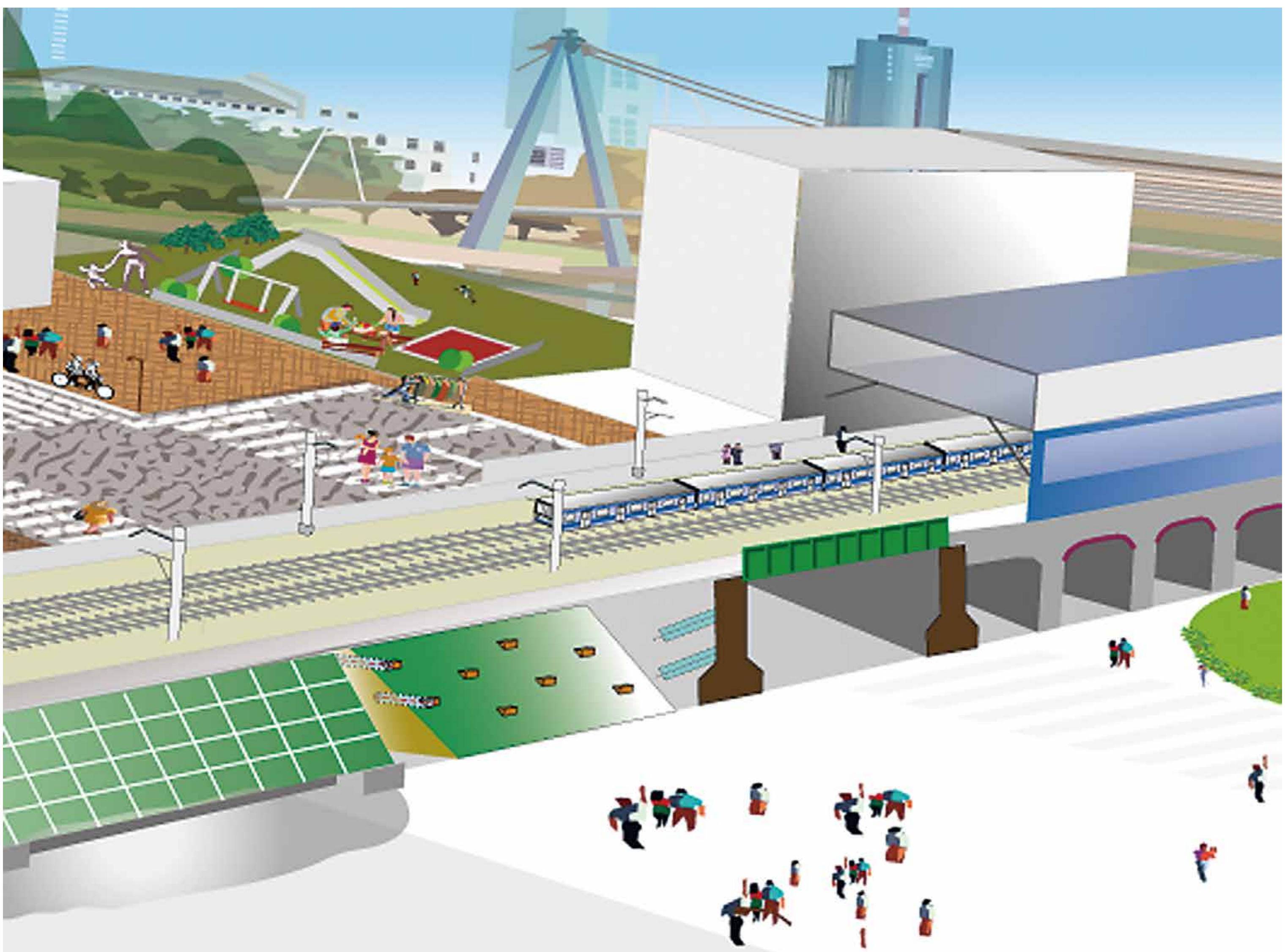
Technology to Enhance the Safety of Railway Structures During Earthquakes



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.

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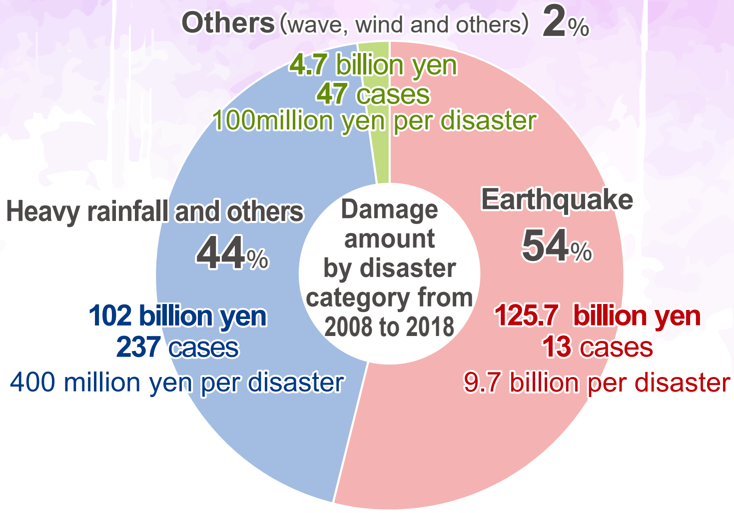
Front cover : Examples of seismic reinforcement of railway facilities

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 years[1].



Cost of damages to railway facilities by natural disasters[1]

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
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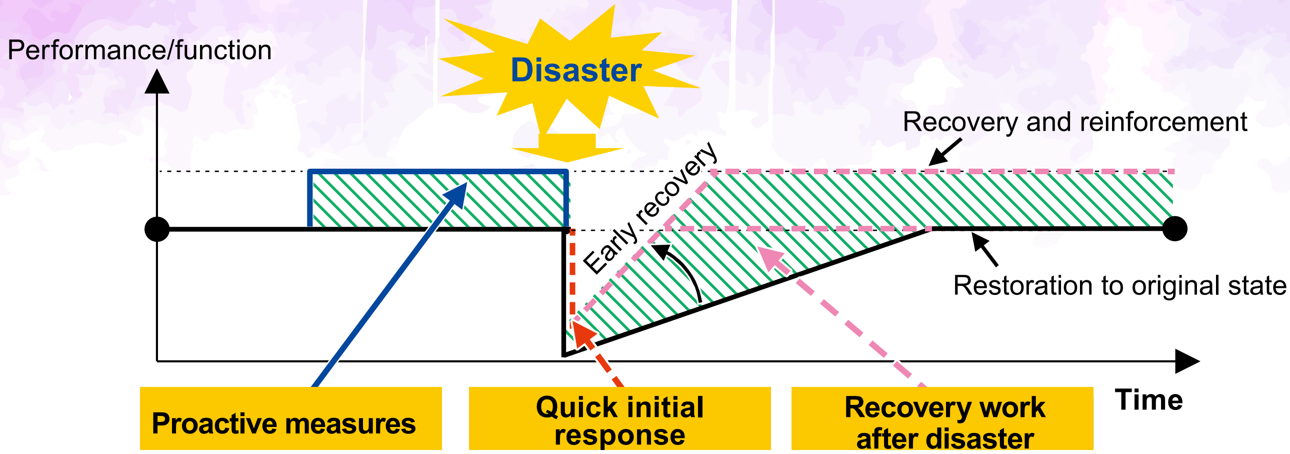
Message from Managing Editor Dr. Toru MIYAUCHI

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 disaster[2)]

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 area[2)].

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.

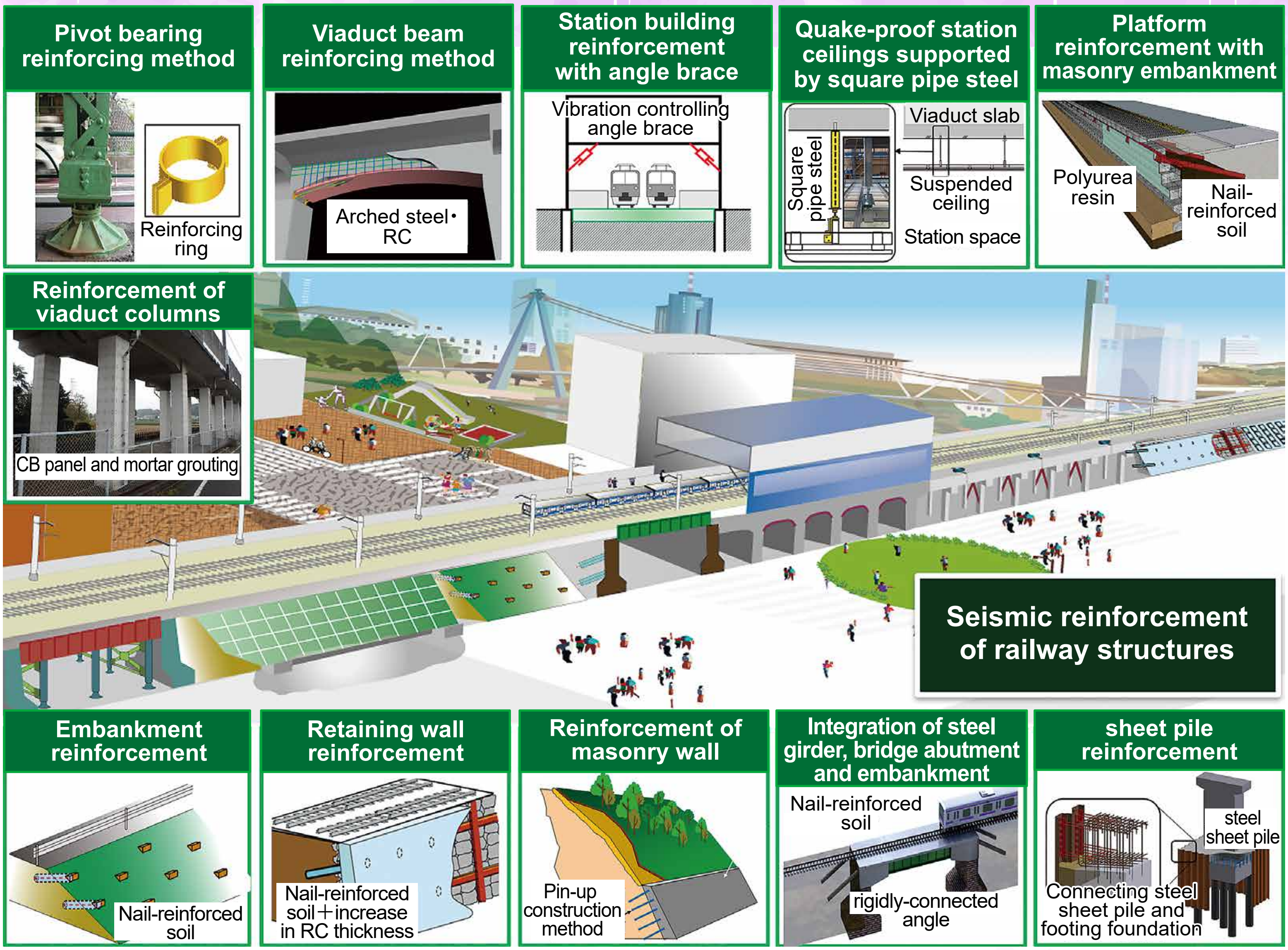
Proactive measures include detecting vulnerable points in advance and upgrading structures to make them more quake-resistant, i.e., advance diagnosis and earthquake-proof reinforcement. A quick initial response involves slowing down or stopping trains based on real-time quake information, and estimating 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



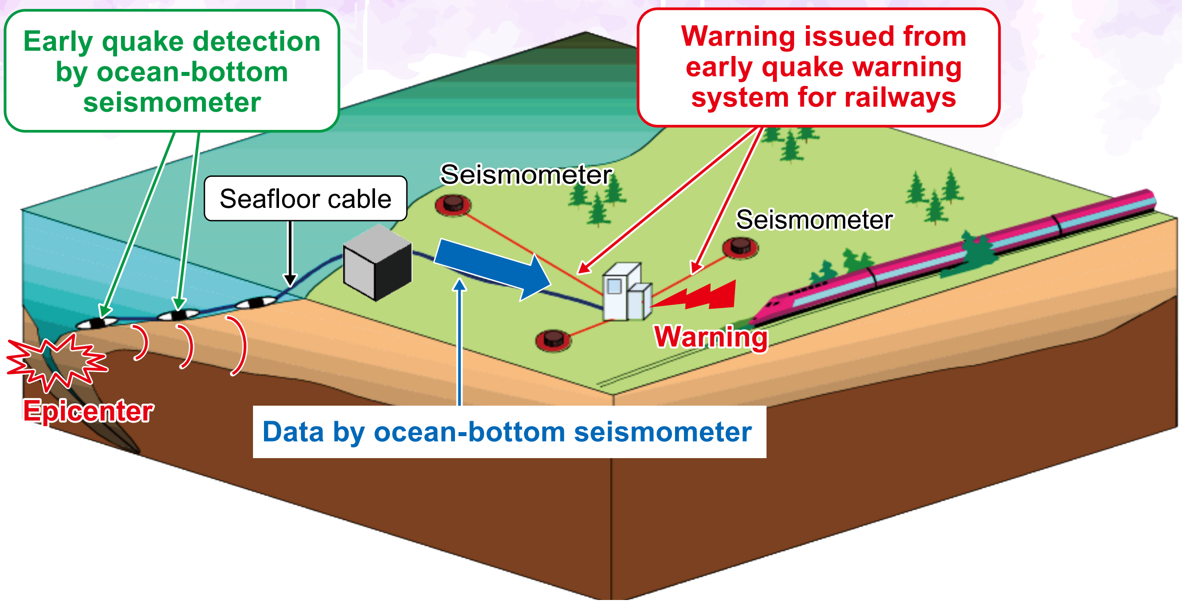
Examples of seismic reinforcement of railway facilities

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 data[8)]

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 2018[7)].

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

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

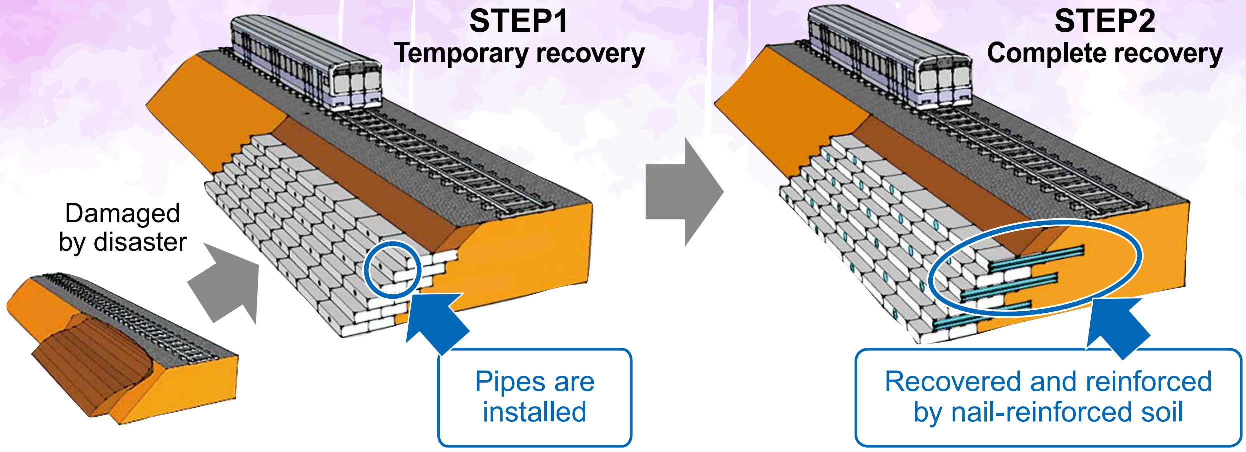
In the aftermath of a disaster, the RTRI immediately initiates support measures to aid the recovery efforts of railway operators. During the Kumamoto Earthquake on April 14, 2016, pillars of RC rigid-frame elevated structures and bearings of Kyushu Shinkansen were damaged between the Shin-Tamana and 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 27[10)].

(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.

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Seismic Stability of Railway Structures on Irregularly Layered Grounds

It is important to accurately understand the seismic behavior of the ground and structures to secure the seismic stability of railway systems. A ground formed on a hard, sloping basement layer is called an irregularly layered ground. On the ground with such a structure, seismic ground motion is likely to be locally amplified and may cause serious damage to railway systems. This paper describes how to accurately and efficiently detect the profile of irregular layered ground to secure the seismic safety of railway structures on an irregularly layered ground.

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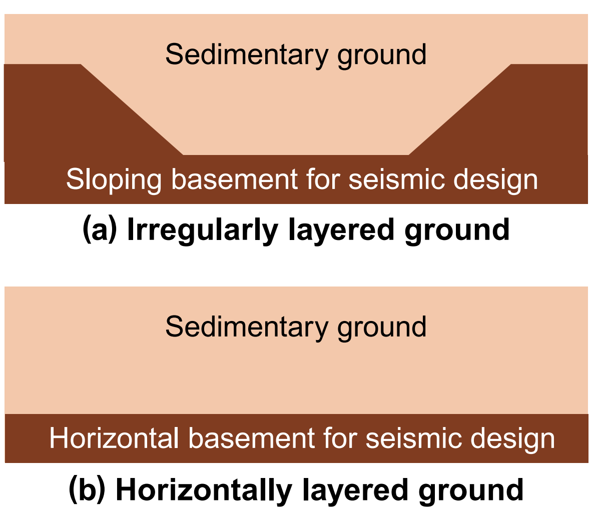
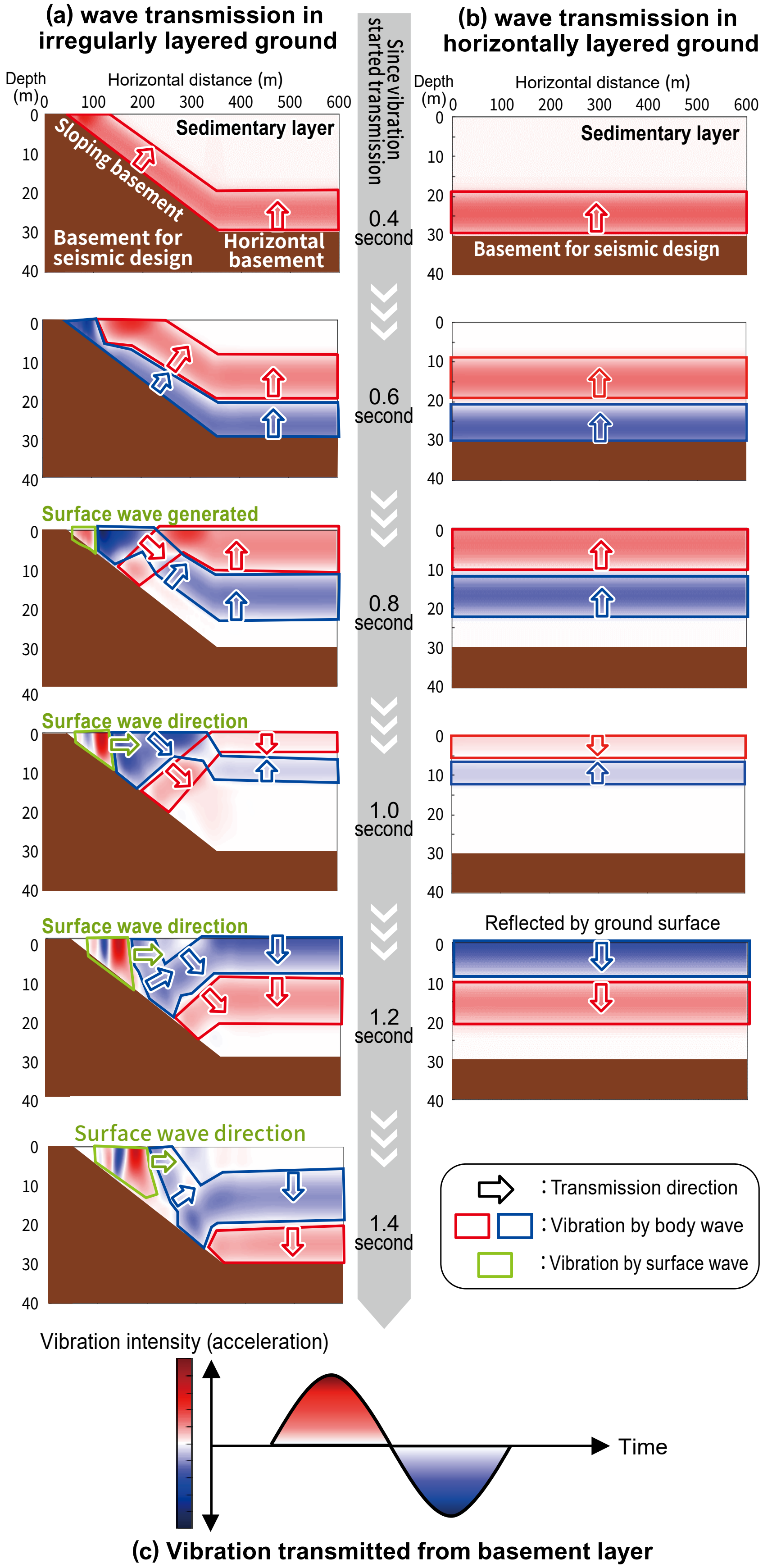


Irregularly layered ground and horizontally layered ground

Introduction

To design railway structures with high seismic stability, it is important to accurately understand seismic ground motion that occurs at construction sites. To achieve this, it is necessary to accurately detect the stratal organization, which significantly affects seismic ground motion.

At the point where the hard-subsurface basement layer (which is used as the basement for seismic design) inclines (*Irregularly layered ground and horizontally layered ground(a)*), ground motion is likely to be intensified, compared to that where the ground is horizontal, as shown in *Irregularly layered ground and horizontally layered ground (b)*. In earthquake engineering, such ground is called an "irregularly layered ground". Because irregularly layered grounds are found in many areas in mountainous countries, such as Japan, buildings and structures need to be carefully designed for improved earthquake-resistant performance.



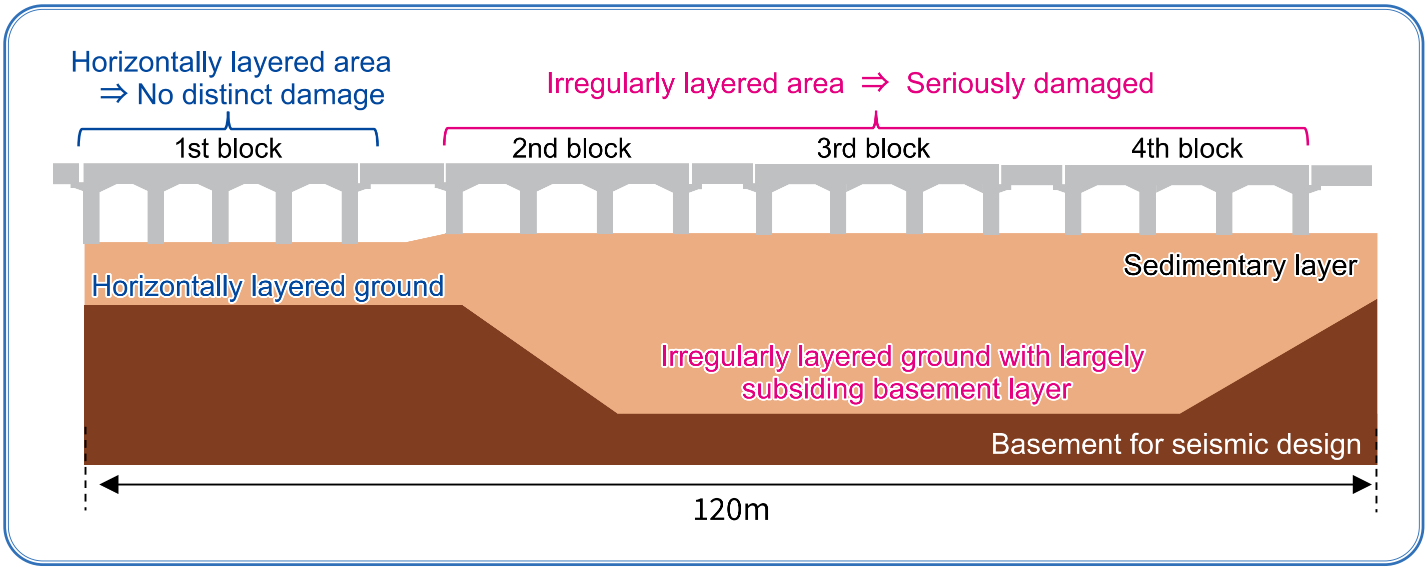
Simulation of wave travelling through irregularly layered ground and horizontally layered

Vibration propagated though irregular subsurface structures

Simulation of wave travelling through irregularly layered ground and horizontally layered (a) and *(b)* shows how seismic waves travel through irregularly and horizontally layered grounds, respectively. Here, a simple sine wave, as shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (c)*, was applied from the lower part of the basement layer (depth:40 m) and wave propagation was simulated. In *Simulation of wave travelling through irregularly layered ground and horizontally layered(a)* and *(b)*, the seismic intensity of waves traveling through the ground is indicated by red and blue colors and their gradations.

In the horizontally layered ground shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (b)*, a horizontally stretched red-colored band appears at the lower part of the sedimentary layer, 0.4 s after the transmission started. This indicates that the waves travel through the layer in the upward direction. At this stage, the waves shown in blue were not yet transmitted into the sedimentary layer. At 0.8 s, the figure shows red and blue bands, and this indicates that all the waves shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (c)* are transmitted in the upward direction. Furthermore, at 1.2 s, the figure shows that positions of the red and blue bands were switched. This implies that upward waves are reflected at the ground surface and change their traveling direction downward. Waves that travel through the ground by repeating reflections are called body waves. *Simulation of wave travelling through irregularly layered ground and horizontally layered* shows the body waves represented by the red and blue boxes.

In the irregular subsurface structures shown in *Simulation of wave travelling*



Damage to structures by local seismic amplification on irregularly layered ground

through irregularly layered ground and horizontally layered (a), the body waves travel through the sedimentary layer. However, on the left side of the ground, a slanted red band appeared along the sloping basement layer, and the body waves were transmitted in the upper diagonal direction. Body waves traveling in the diagonal direction were reflected by the ground surface earlier than those on the right-hand side of the horizontal layer ground. The body waves travel through the sedimentary layer in complicated patterns, including both upward and downward transmissions (from 0.8 s).

On the irregularly layered ground, waves are generated in 0.8 s, close to the ground surface, approximately 50–100 m from the left. These waves travel in the horizontal direction near the surface, differently from body waves, and they are called "surface waves". At the irregularly layered ground, these surface waves are generated at boundary areas between the near-surface basement layer and the sedimentary layer. In *Simulation of wave travelling through irregularly layered ground and horizontally layered (a)*, the surface waves are shown by a green box. Surface waves travel along the ground surface to horizontally layered sections depending on the angles of the sloping basement.

This simulation assumes that the shaking shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (c)* travels from the base. However, the shaking caused by actual earthquakes is more complicated, including different patterns of body and surface waves. Consequently, the body and surface waves overlap and sometimes cause intense waves in certain areas.

Damage to railway structures built on irregular subsurface structures

In Japan, earthquake damage to railway structures is caused by irregularly layered ground. In the offshore earthquake that took place near Chiba prefecture in 1987 (magnitude 6.7), the damage to railway structures was located on the irregularly layered ground, where the basement layer largely subsides (*Damage to structures by local seismic amplification on irregularly layered ground*). The damage was particularly serious in the 2nd to 4th blocks, which were located on the irregularly layered ground, whereas distinct damage was not confirmed in the 1st block located on the horizontally layered ground. As shown in this case, even if they are located in approximately the same area, the extent of damage to structures may differ depending on the slope angles of the basement layer.

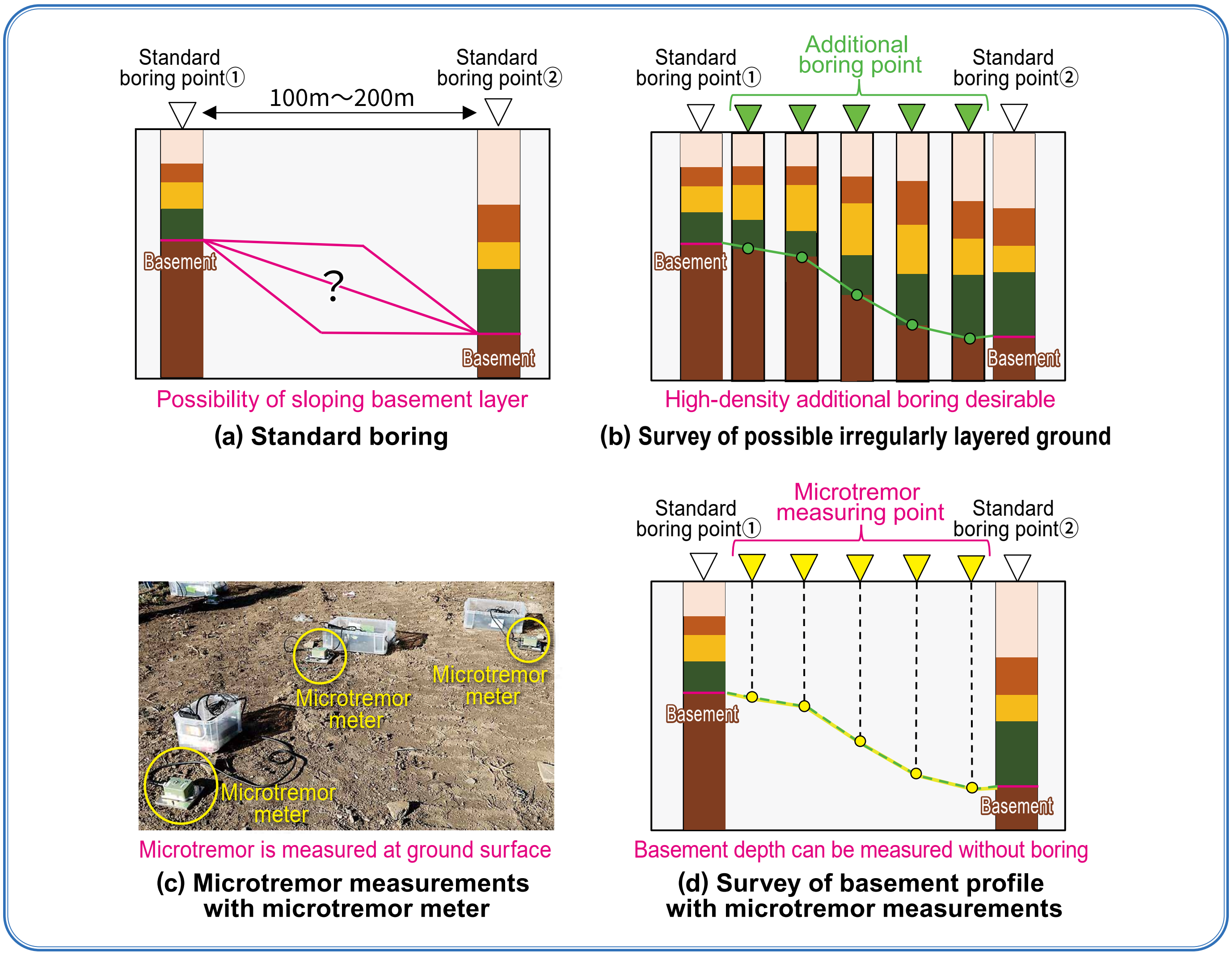
Irregularly layered-ground-detection method

The Railway Technical Research Institute (RTRI) has developed methods to calculate the seismic behavior of the ground and structures to improve the seismic stability of railway structures built on irregularly layered grounds. To apply such methods, we should understand the structures of irregular ground in advance. Thus, RTRI proposed the following method to easily and accurately survey irregular ground structures.

Usually, the depth of the basement layer is directly measured by conducting boring investigations. The boring investigation is normally conducted at 100–200-meter intervals as shown in *Ground survey method using microtremor measurements instead of boring exploration (b)* , but it does not determine the depths of the layers in between. If the results of the boring investigation indicate that the sediment structures of the area might be irregular, additional investigations should be conducted to understand the contour of the layer more accurately. Because additional boring investigations require considerable labor and cost, there are limits to conducting these additional investigations.

For this reason, RTRI developed a survey method using a small-sized portable device For microtremor measurements. The depth of the basement layer directly beneath the device can be estimated by placing this device on the ground surface for approximately 30 min and measuring the microtremor, as shown in *Ground survey method using microtremor measurements instead of boring exploration (d)*.

As shown in *Survey of basement profile with microtremor measurements (a)*, microtremors include waves with various periods and amplitudes. By analyzing the microtremor through spectrum analysis, the relationships between the amplitudes and periods were obtained. As indicated in *Survey of basement profile with microtremor measurements (b)*, the results of the spectral analysis at two different points on irregularly layered ground show different peak periods that depend on the depth of the basement layer. RTRI conducted microtremor measurements and numerical simulations in many areas on an irregularly layered ground and determined the relationship between the basement depth difference and the peak period difference of two points (*Survey of basement profile with microtremor*



Ground survey method using microtremor measurements instead of boring exploration

measurements(c)). Applying this relationship to survey data, the profiles of irregularly layered ground can be accurately understood by measuring microtremors at several points between boring points.

Conclusion

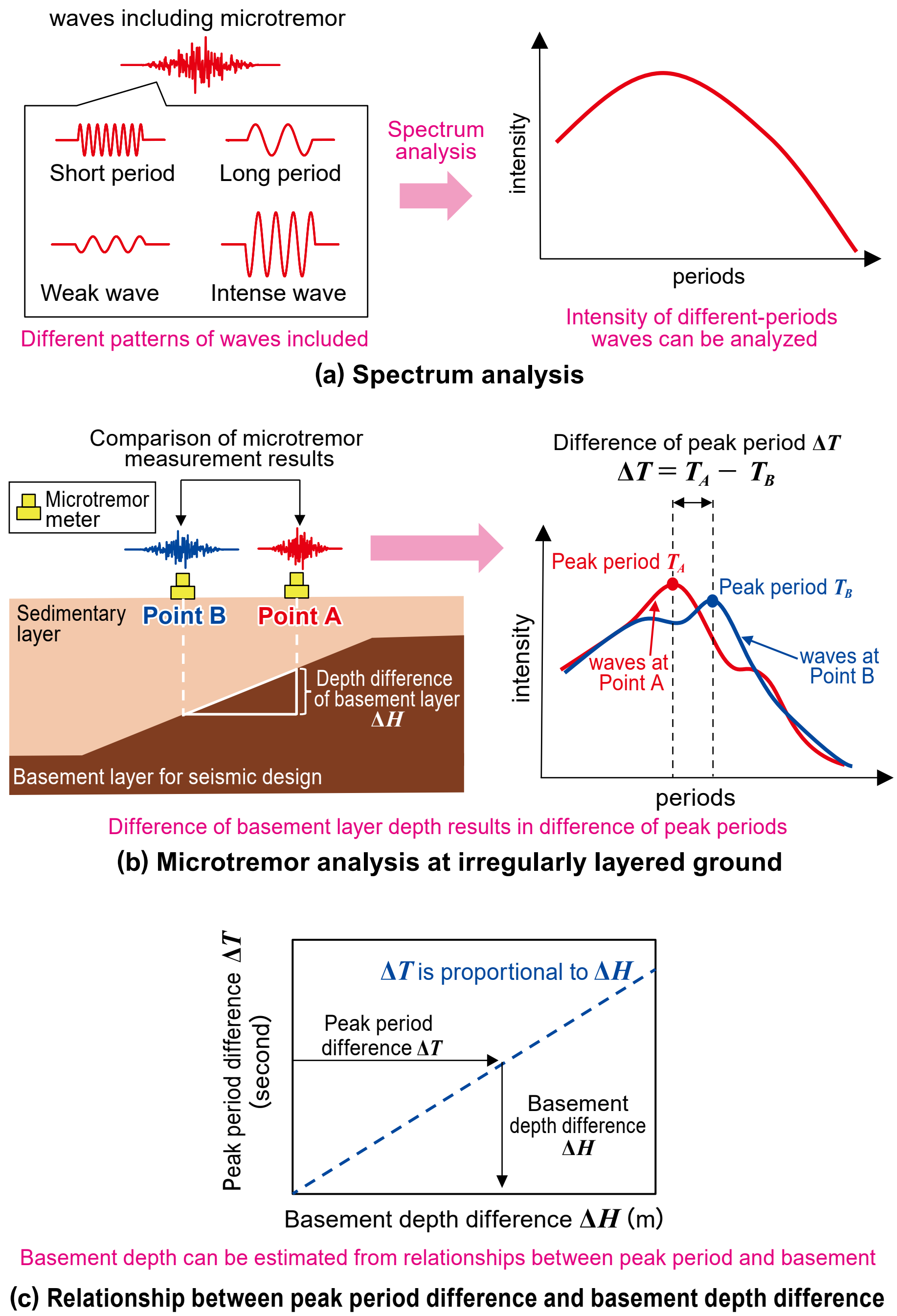
This paper describes seismic ground motion on irregularly layered grounds and the profiles of such irregular grounds, which is one of RTRI's research projects conducted to secure the seismic stability of railway structures. Through this method, the intensity of shaking on irregular grounds can be calculated more easily and accurately, and safer structural designs are possible.

Boring investigation

A survey method was used to measure the ground structure conditions and depth of the basement layers used for seismic design. The data, including soil strength, were obtained from soil samples collected at a depth of 1 m in holes that were vertically drilled at the survey points.

Microtremor

Microwaves are caused by a variety of movements, such as natural phenomena including ocean waves, winds, and human activities, including automobile running. In contrast to earthquakes, microtremors can be measured at any time.



Survey of basement profile with microtremor measurements

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In Japan, many rocking-pier steel railway bridges were built, mainly from the Meiji to the early Showa period. Fortunately, only a few of these bridges have been affected by earthquake damage. However, if damage is incurred by large-scale earthquakes, collapse is possible. Therefore, the seismic performance of these bridges was verified and reinforcement was implemented where necessary. For seismic diagnosis, the assessment is conducted on weaker sections, which are subsequently reinforced as necessary. This study introduces methods for seismic diagnosis and reinforcement.

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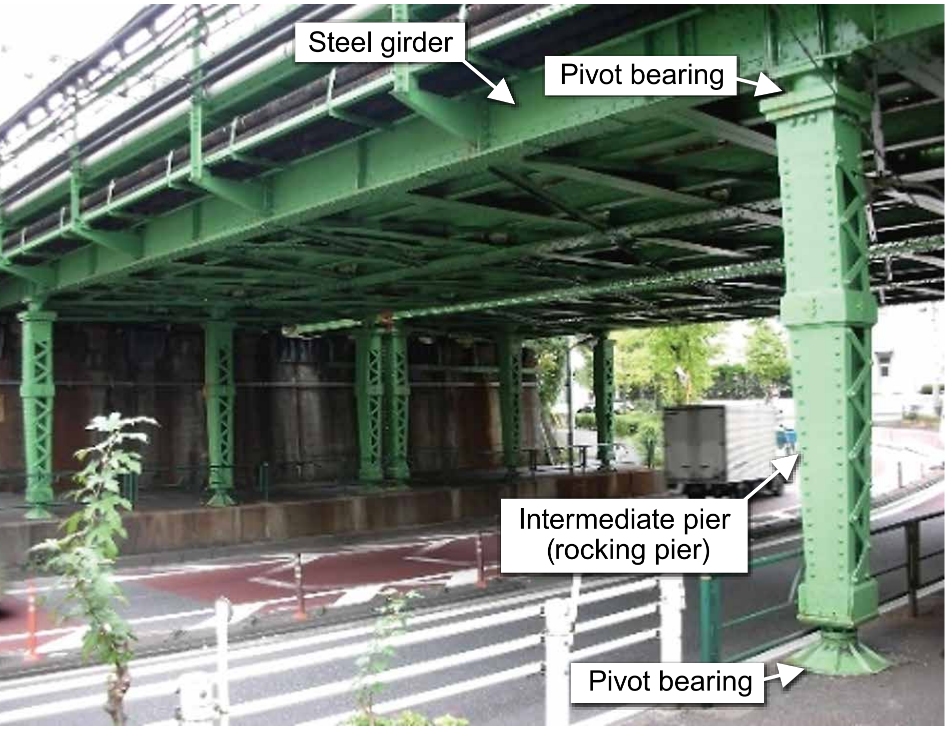
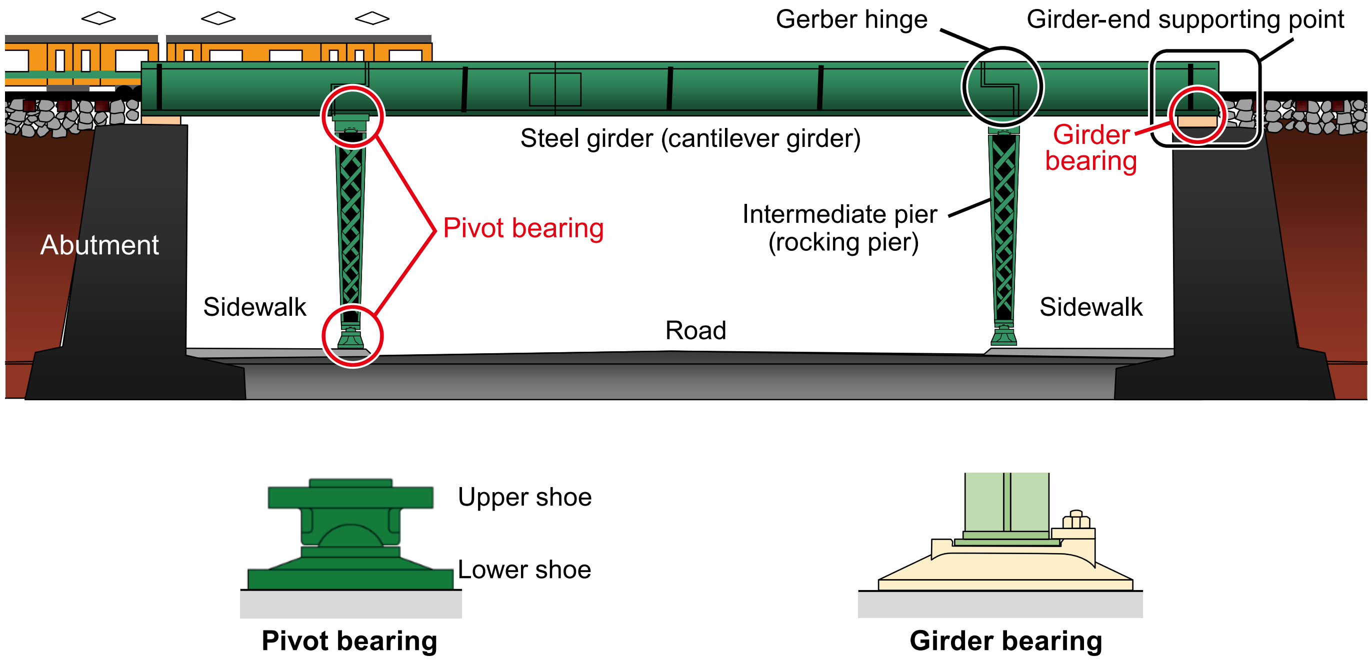
Seismic Diagnosis and Reinforcement of Steel Railway Bridges in Urban Areas



A bridge supported by rocking pier

Introduction

In urban areas, many railway lines were elevated, from the Meiji to the early Showa period. Along these lines, steel bridges were constructed at points where tracks passed over roads or other tracks. In sections where the line must pass over a wide road or a multiple-track railway line, a longer bridge is required. In such cases, bridge piers are constructed in the middle of the bridge (intermediate pier) and support the bridge girder, in addition to the abutment on both ends (*A bridge supported by rocking pier* and *Overview of a bridge supported by rocking pier*). "Rocking piers" with pivot bearings at the top and bottom are often used as intermediate piers to support longer bridges. The pivot bearings can rotate in all directions by combining sphere-



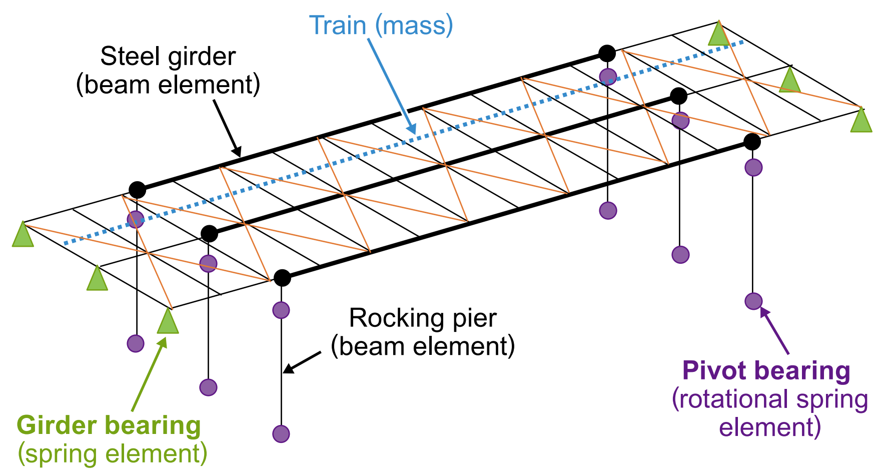
Overview of a bridge supported by rocking pier

shaped lower shoes and depressed upper shoes. Since rocking piers render bridges as statically determinate structures, the design calculations were conducted easily in the past even with the lack of well-developed computers.

When a rocking-pier bridge is shaken by an earthquake, only the supporting points at both ends of the bridge resist lateral force, but the rocking piers do not. Because of this property, once an earthquake occurs, the girder bearings are likely to be damaged, the girder is likely to move laterally, and it is possible that rocking piers might collapse causing the bridge to fall.

In the past, railway bridges did not suffer any serious damage due to earthquakes, such as collapse. However, in the Kumamoto Earthquake of 2016, one road bridge collapsed[1]. Following this disaster, in 2018, rocking-pier bridges were included among the facilities to be regulated by the Government Order on Seismic Reinforcement of Specific Railway Facilities. Since then, seismic diagnosis has been prioritized, and seismic reinforcement has also been implemented depending on the results of the diagnosis.

This study describes seismic diagnosis and reinforcement methods for rocking-pier bridges.

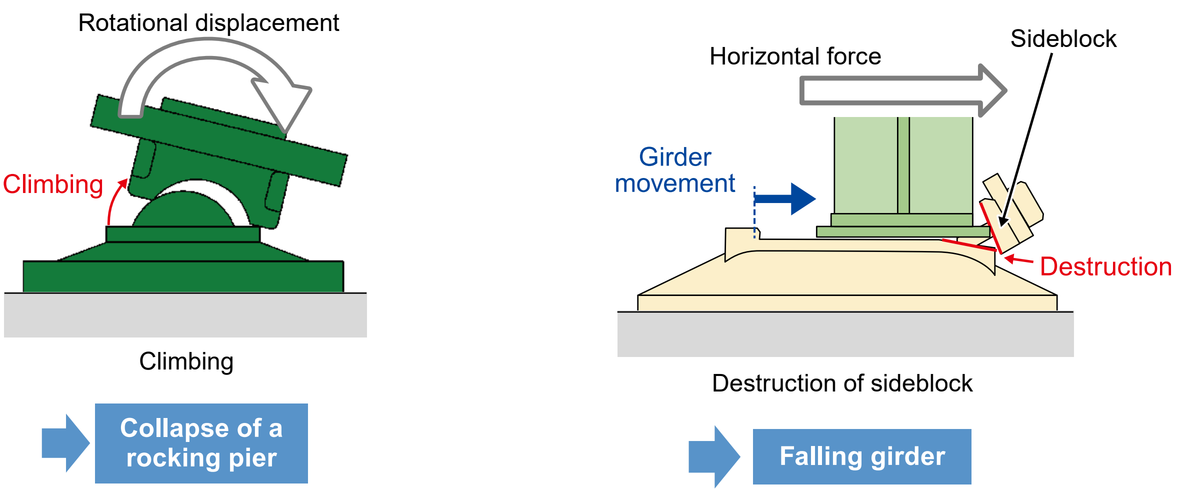


Analysis model

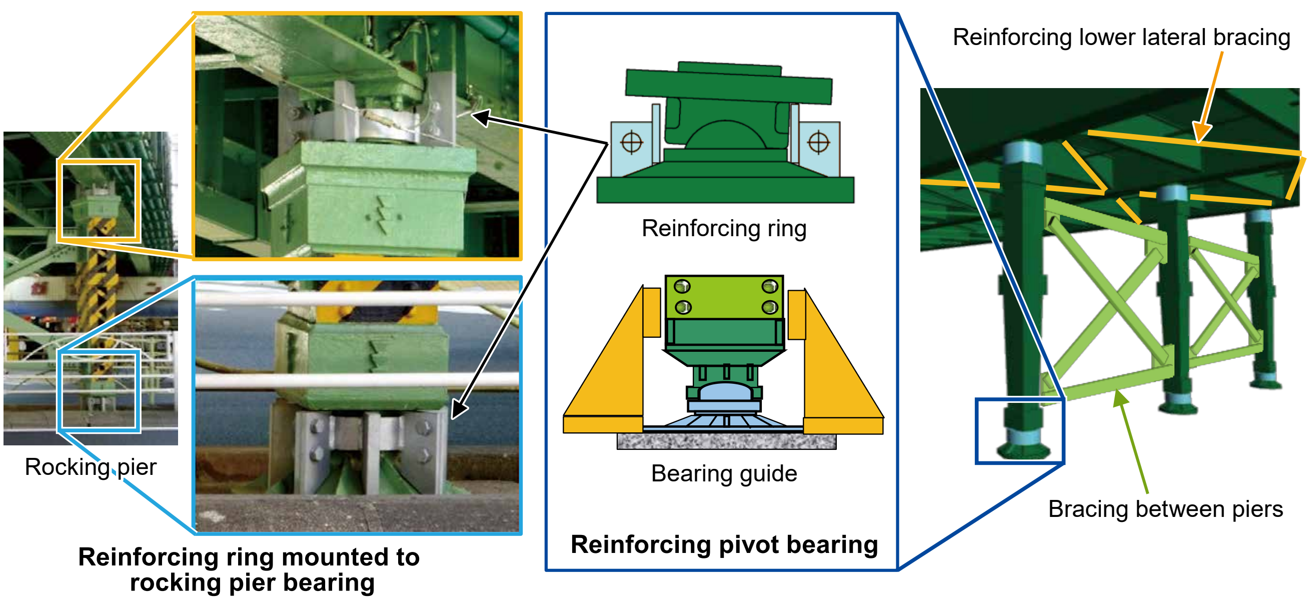
Seismic diagnosis method

In this study, for seismic diagnosis, a bridge is first modeled, as shown in *Analysis model* ; earthquake motion is then applied to the modeled bridge, and its impact is analyzed. Through the analysis, we investigated damage to pivot bearings, girder bearings at bridge ends, steel girders, rocking piers, and Gerber hinges.

For the pivot bearing, we determined whether the upper shoe climbs up the lower shoe. As shown in *Climbing of pivot bearing* , when the displacement of the steel girder increases, the rocking pier tends to tilt, and the rotational displacement of the pivot bearing increases. Eventually, the upper shoe climbs up the lower shoe and



Climbing of pivot bearing **Destruction of girder bearing and girder movement**



Prevention of rocking pier collapse

causes the collapse of the rocking pier.

For the girder bearing, as *Destruction of girder bearing and girder movement* indicates, we determined whether the side block that constrains the girder displacement is not destroyed by the lateral movement of the girder. Even if the side block is destroyed, the bridge is unlikely to collapse when the girder displacement is small, and the girder ends remain on the abutment.

Policy of seismic reinforcement

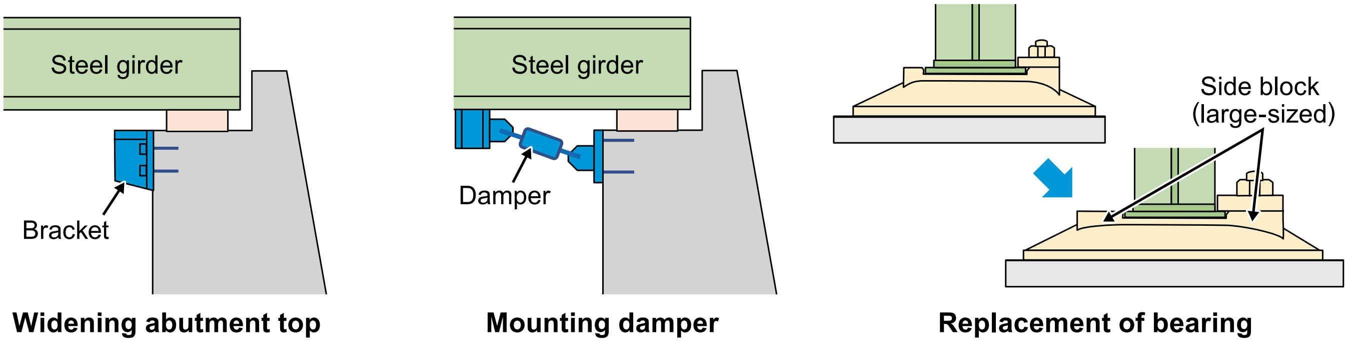
Since most rocking-pier bridges were built much earlier, they have not been designed to endure large-scale earthquakes. Therefore, through seismic diagnosis, some of the bridges were found to be susceptible to collapse if damaged by a large-scale earthquake hence the need for reinforcement.

The implementation of seismic reinforcement prevents collapse and enables early restart of train operations, depending on the importance of each line. We describe two seismic reinforcement measures: prevention of rocking-pier collapse and girder falling at the girder ends.

Prevention of rocking-pier collapse

By installing reinforcement rings or shoe guides on pivot bearings, the collapse of the rocking pier is prevented as shown in *Prevention of rocking pier collapse*.

Reinforcement rings prevent detachment



Measures to prevent girder falling at the girder-end supporting point

of the upper shoe of the pivot bearing from the lower shoe without losing ordinary rotating function[2]. Even if the upper shoe rises and comes off in an earthquake, the shoe guide prevents displacement of the bridge pier and guides it back to the normal position.

If this reinforcement is insufficient to prevent the collapse of the rocking pier, braces are installed between the piers. Alternatively, the lower lateral bracing of the steel girder is reinforced to reduce the lateral deflection of the steel girder and consequently reduced the rotating displacement of the pivot bearing.

Prevention of steel girder end support collapse

If there is a possibility that bearings at girder ends might be destroyed or a girder might fall from the abutment during an earthquake, the measures shown in *Measures to prevent girder falling at the girder-end supporting point* may be taken.

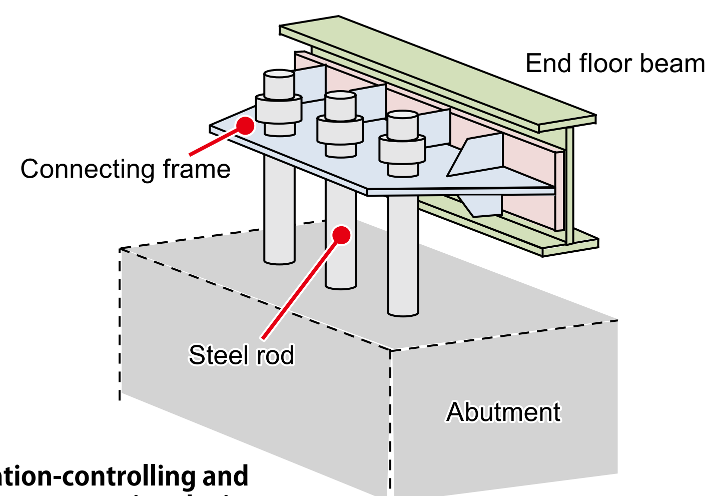
First, by mounting a bracket on the front side of the bridge abutment, the abutment top is widened and girder falling is prevented even if the bearing is destroyed and the girder is moved. Second, a damper absorbs the earthquake energy transmitted through the steel girder and controls the movement of the steel girder. Third, if the bearing is replaced by one with larger side blocks, it is less likely to be destroyed.

In urban areas, it might be difficult to ensure sufficient workspace or place to mount these devices, because bridges either have narrow abutment top spaces or under-bridge spaces are occupied by roads. However, because many urban railway lines are heavily used, minimizing the movement of the steel girder is a requirement to reinstate train operation as soon as possible after an earthquake. To meet these requirements, a new device to control vibrations and prevent bridge collapse has been developed[3].

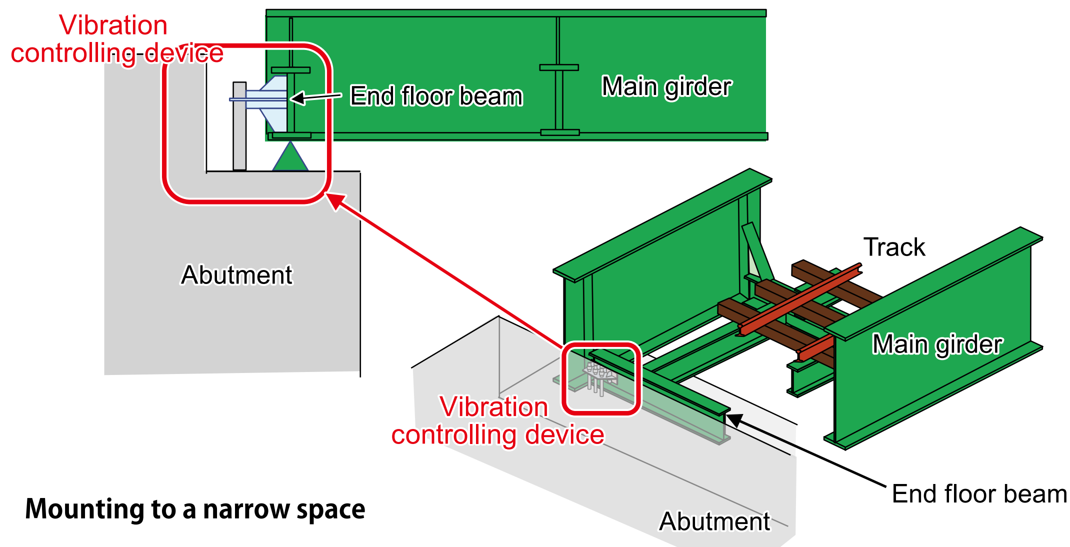
As shown in *Vibration-controlling and collapse prevention device* , the steel rods set up on the abutment are fixed on a steel frame and mounted onto the end of the steel girder. This device has the following two features:

First, since the steel rods absorb earthquake energy by deforming themselves and controlling the displacement of the steel girders, the earthquake damage is expected to recover early. Furthermore, as the steel rods extend, they are unlikely to be fractured by serious earthquake shaking, and the fall of the steel girder is likely to be avoided.

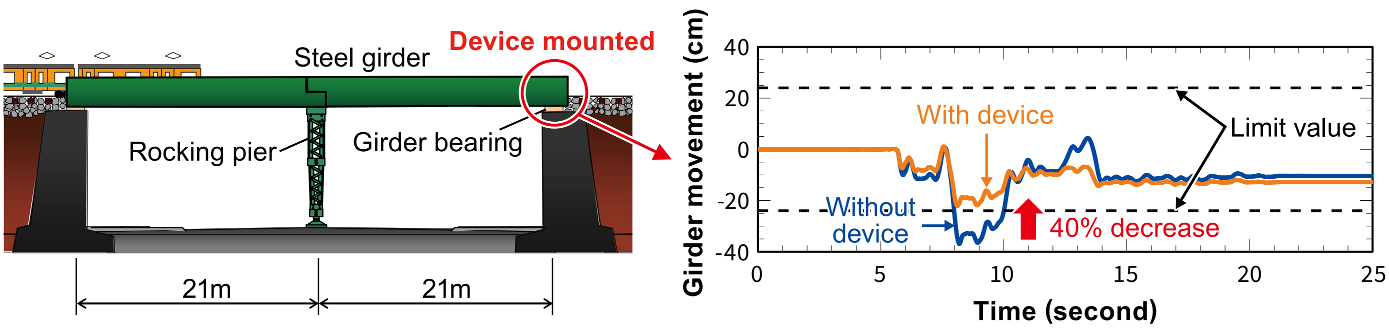
Second, owing to its small size, as shown in *Mounting to a narrow space* , this system can be mounted onto a narrow abutment top, and because it is placed on the abutment, it does not protrude into the undergirder space.



Vibration-controlling and collapse prevention device



Mounting to a narrow space



Verifying the effect by dynamic analysis

By analyzing the difference in the girder movement of two-span bridges mounted with this device, its effectiveness was validated. *Verifying the effect by dynamic analysis* compares the displacement of girders with or without the device when girder bearings at the bridge ends are destroyed by an earthquake. In this case, installing the device reduced girder displacement by 40%, from a maximum of 37 to 22 cm.

Conclusion

This study describes methods for seismic diagnosis and reinforcement of rocking-pier bridges in urban areas. It is important to identify weak sections by seismic diagnosis and implement measures that consider the balance of the entire structure and restraints in the construction and repair work. We will continue to develop seismic diagnosis methods that can be applied to different types of structures, and develop effective, low-cost reinforcement methods.

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Seismic Reinforcement of Abutments and Retaining Walls in Narrow Space

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Foundation and Geotechnical Engineering,
Structures Technology Division

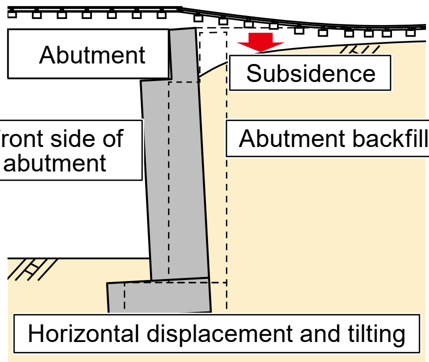
Reinforcement of abutments and retaining walls to improve earthquake resistance involves major work at the front side of the structures. If the structure is located in a narrow space where land is limited, especially in urban areas, it is difficult to provide reinforcement. However, the structures in urban areas often require seismic reinforcement. Hence, it is necessary to develop cost-effective seismic reinforcement methods that can be implemented even in narrow spaces. This paper describes seismic reinforcement methods for abutment and retaining walls developed by RTRI that can minimize the workspace on the front side of structures during construction.

A collapsed retaining wall (Great Hanshin Earthquake in 1995)[1)]

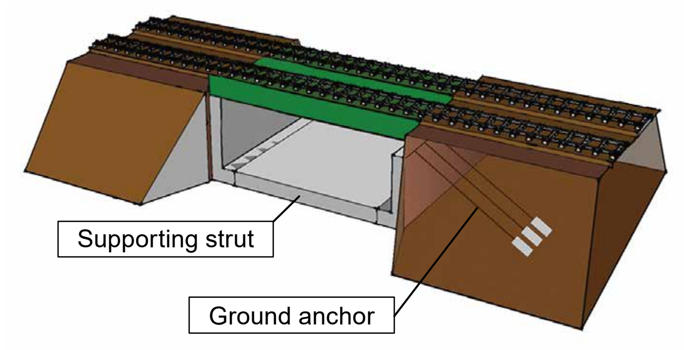
Introduction

The abutments, retaining walls, bridges, and viaducts[1)] suffered serious damage during the Great Hanshin Earthquake in 1995 (*A collapsed retaining wall (Great Hanshin Earthquake in 1995)*). After the disaster, the existing railway structures were reinforced to improve their seismic performance.

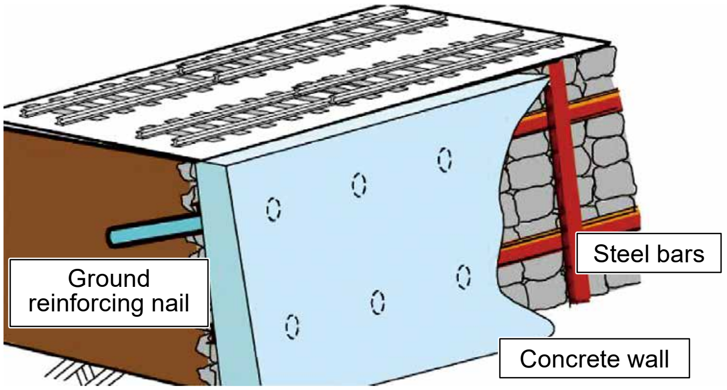
Subsidence at the abutment backfill depicts a case of damage to an abutment during an earthquake. In this case, the abutment was pushed by the embankment behind resulting in the abutment being laterally displaced or tilted; as a result, the embankment subsided. Railway structures damaged in this manner may lead to the deformation of tracks, seriously threatening the safety of trains running. Therefore, in recent years, seismic reinforcement plans have been implemented for existing abutments.



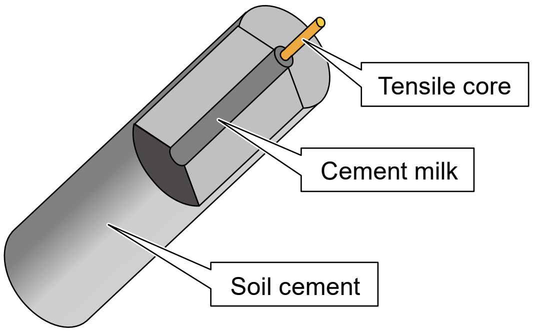
Subsidence at the abutment backfill



Seismic reinforcement of an existing abutment [2)]



Seismic reinforcement of an existing retaining wall [2)]



Cross-section of ground reinforcing nail

Meanwhile, there are more than 250 thousand retaining walls along railway lines across Japan, most of which are masonry walls. The masonry retaining walls were built before concrete walls became popular. However, several masonry walls have been reported to collapse during large earthquakes. It is necessary to develop low-cost methods for seismic reinforcement of a vast number of such retaining walls along railway lines.

Existing methods

In the past, abutments were generally reinforced by supporting-strut and ground-anchor methods. In the supporting-strut method, a reinforced concrete slab is placed between the abutments to support them. The ground-anchor method uses high-strength steel tension rods to fix abutments to the ground (*Seismic reinforcement of an existing abutment*). To reinforce retaining walls, in many cases, concrete walls were built on the front side of the retaining walls, as shown in *Seismic reinforcement of an existing retaining wall*, and ground reinforcing nails in *Cross-section of ground reinforcing nail* were placed to ensure the stability of the concrete walls.

However, these methods require a wide workspace in front of the structures. Therefore, these methods making it difficult to implement them in narrow places where there are roads or tracks in front of abutments or retaining walls. However, because most structures to be given priority in reinforcement are in urban areas where they are often confined to narrow spaces, a reinforcement method that is inexpensive and can be implemented in such spaces is to be developed.

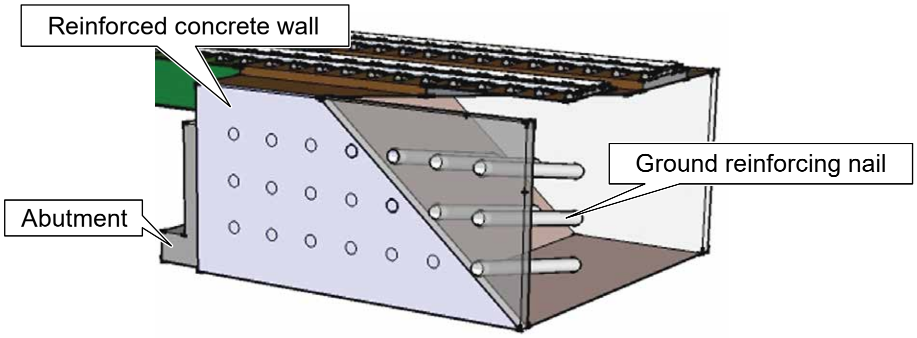
This paper explains seismic reinforcement methods for abutments and retaining walls, that can be implemented even in narrow workspaces in front side of the structures, has been presented.

Seismic reinforcement methods for the abutment

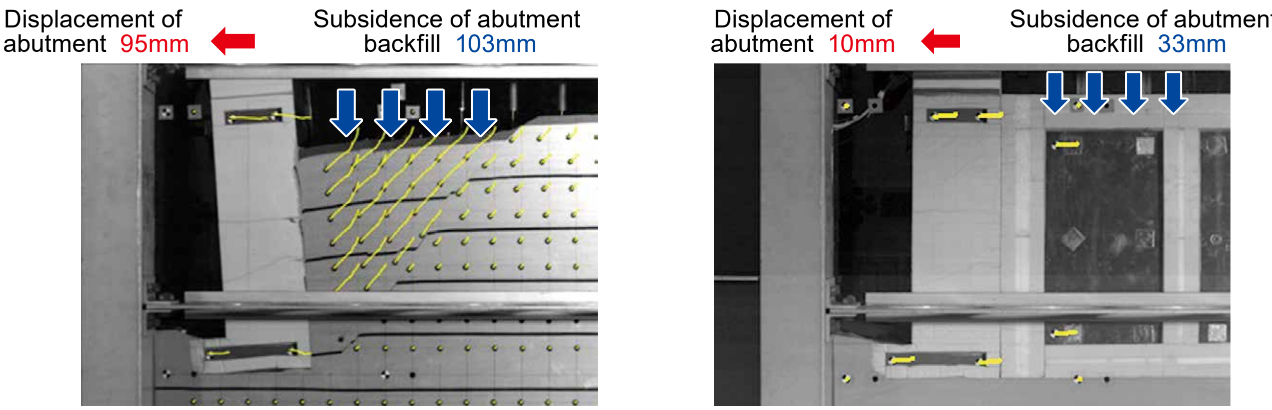
(1) Integrating ground-reinforcing nails and abutment

In this method, construction begins from the backside of embankment of the abutment (*Seismic reinforcement by integrating ground reinforcing nails and abutment*). By integrating the abutment, concrete wall, and ground reinforcing nails, the earthquake resistance of the abutment is improved, and it is less likely to collapse, even when hit by a severe earthquake. This method is adopted to reinforce the spots where the earthquake resistance of the wing walls (retaining wall built adjacent to the abutment) is insufficient, and the abutment backfill is likely to flow out through the gap between the wing walls and abutment in the case of an earthquake.

A model shaking experiment to confirm the reinforcing effects is briefly introduced herein. In the experiment, a



Seismic reinforcement by integrating ground reinforcing nails and abutment [2)]



(a) Not reinforced **(b) Reinforced**

Performance test for seismic reinforcement of abutment[2)]
(Integrating ground reinforcing nails and abutment)

1/8-scale abutment model was shaken by a simulated earthquake on medium-sized shaking machine of the RTRI (*Performance test for seismic reinforcement of abutment (Integrating ground reinforcing nails and abutment)*). The results confirmed that the residual displacement (final displacement amount of the abutment after shaking) and subsidence on the abutment backfill were significantly reduced due to reinforcement. The application of this method to actual structures is currently being planned. The structures to be reinforced are bridges over railway tracks and their embankments.

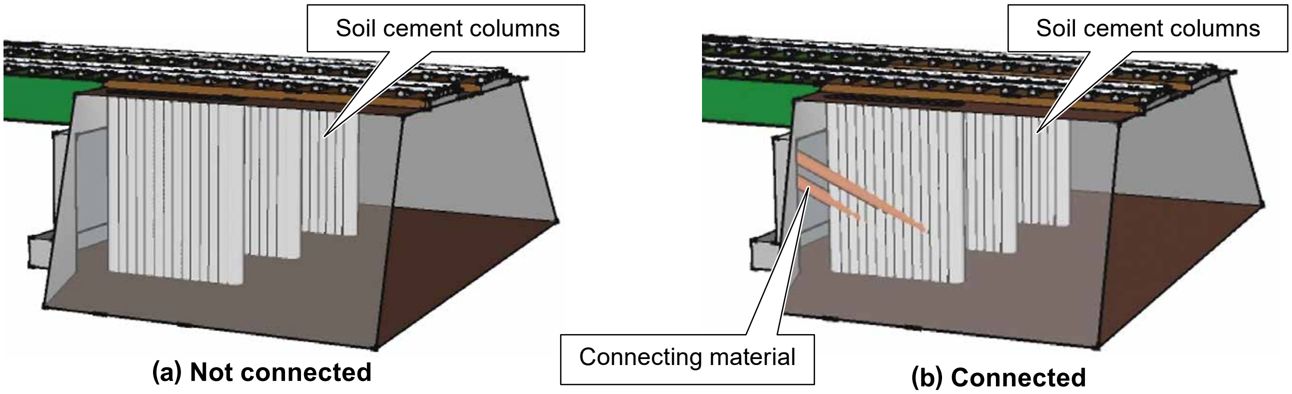
(2) Soil-improvement of abutment backfill

In this method, soil cement columns are placed in the abutment backfill. These columns restrict abutment deformation and backfill subsidence[2),3)] (*Seismic reinforcement by soil-improvement of abutment backfill (a)*). This method is applied mostly to abutment backfill that are built with low-quality materials. Because soil cement columns are placed from the track face (top of the abutment backfill), workspace at the front side of the abutment is not required. Columns can be placed using low-height machinery that does not reach the overhead lines. Furthermore, if the abutment does not have sufficient earthquake resistance and is likely to collapse by overturning in an earthquake, it can be reinforced by connecting the abutment with columns using connecting material (PC steel rods inserted and fixed with mortar) (*Seismic reinforcement by soil-improvement of abutment backfill (b)*). Such cases require workspace in front side of the abutment.

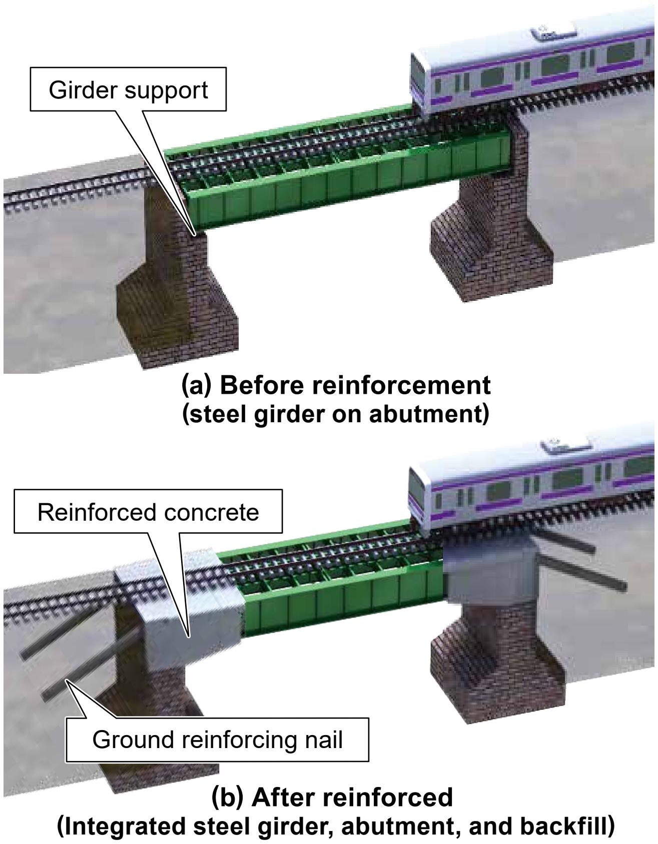
Model shaking experiments have confirmed that the seismic resistance of the abutment is improved by this type of reinforcement. Furthermore, by connecting the abutment and soil cement columns, the effect of suppressing the abutment collapse by overturning was demonstrated, which indicates that the seismic resistance was significantly improved. This method has already been used to reinforce abutments of an actual railway line[3)]. Here, only one row of columns was placed on each side of the track, but two were built at the location where there is a wide space between tracks on a double track.

(3) Integrating steel girder-abutment-backfill

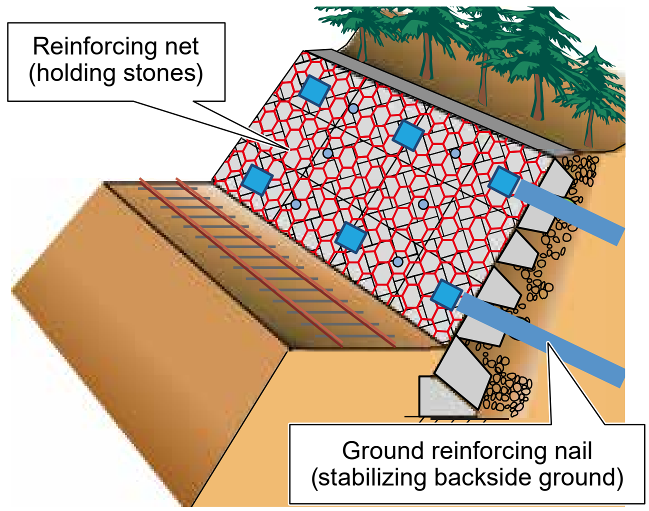
This method integrates steel girders, abutments, and the abutment backfill with reinforced concrete and ground-reinforcing nails to extend the service life



Seismic reinforcement by soil-improvement of abutment backfill [2)]



Integrating steel girder, abutment and backfill[2)]



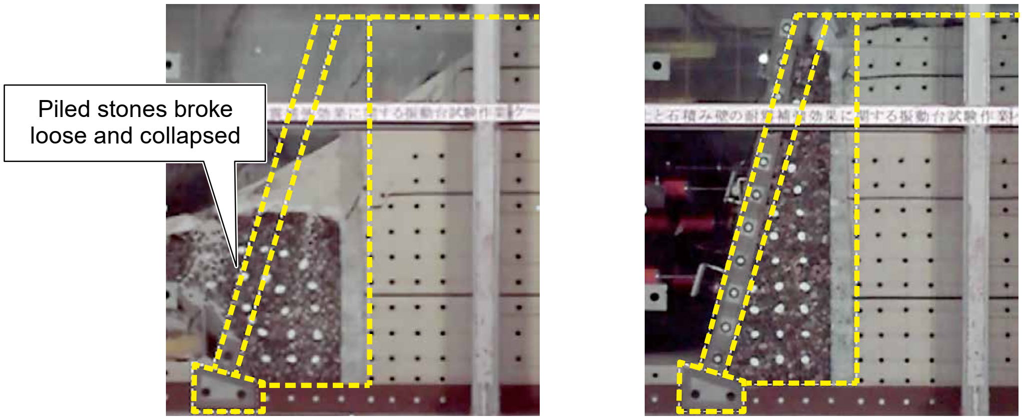
Net-reinforcement method[2)]

and improve the earthquake resistance of old bridges (*Integrating steel girder, abutment and embankment*). As the intersection (including bearings) of the steel girder and abutment is covered with concrete, it reduces maintenance, and the integrated girder and abutment prevent the falling of the girder. Furthermore, by connecting the abutment and backfill with reinforcing nails inserted from the side or front of the abutment, subsidence of the backfill is prevented making the abutment more stable. Because this method is likely to improve earthquake resistance by changing the structure, it is effective in enhancing the seismic performance of steel girders with deteriorated materials or abutments made of bricks and piled stones.

To study the efficiency of this method, model experiments were conducted to investigate the reinforcement of intersection of the girder and abutment. Based on these experiments, basic characteristics such as behavior during an earthquake was confirmed. In addition, a test-purpose bridge was constructed and its performance was verified by continuous observation and loading tests.

This method has been applied to reinforce an actual structure[4)]. Initially, the plan was to replace the bridge. However, by adopting this method, the earthquake resistance of the bridge was improved, and

Shaken with 400 gal　　Shaken with 800 gal



(a) Not reinforced　　(b) Reinforced

Performance test for Net-reinforcement method[2)]
(Yellow broken line indicates the position of retaining wall before shaking)

its service life was extended at a reasonable cost. Through a performance check, it was confirmed that the girder flexure was reduced to 1/2 to 1/3 of the pre-reinforcement, and the noise level during the passing of the train was also lowered.

Seismic reinforcement method for the retaining wall

A reinforcing method called the net reinforcement method has been proposed for the retaining walls in narrow spaces. In this method, the front side of the masonry retaining wall is covered with a wire net to hold piled stones, and ground-reinforcing nails are placed to stabilize the trackside slope (*Net-reinforcement method*). When reinforcing retaining walls with this method, it is not necessary to move obstacles, such as cables, on the front face of the wall or to build concrete forms. Therefore, reinforcement work can be conducted in a narrow space such as a railway track that is laid right in front of a wall.

The effects of the net reinforcement method were confirmed in the model shaking experiments. The experimental results are shown in *Performance test for Net-reinforcement method (Yellow broken line indicates the position of retaining wall before shaking*). After the model retaining wall without any reinforcement was shaken with an acceleration of 400 gal, the piled stones broke loose, and the wall collapsed. However, the model retaining wall reinforced with this method was only slightly deformed even after being shaken intensely with an acceleration of 800 gal. These experiments prove that the retaining wall reinforced with this method can withstand a large earthquake.

The net reinforcement method has already been applied to an actual retaining wall. It is a 7-meter-high masonry retaining wall, and cables are laid at every corner of the surface. Because it is difficult to remove the cables and cover the wall with concrete, the net reinforcement method was adopted, and the cables were left on the wall.

Conclusion

This paper introduced seismic reinforcement methods available for abutments and retaining walls located in narrow spaces. We will collect and analyze cases of reinforcement to further improve the reinforcement methods, and propose methods to choose the best measure.

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Panel discussion at Plenary Session 2

WCRR 2022 Held in Birmingham

WCRR 2022, the 13th World Congress on Railway Research took place from June 6 to 10, 2022 in the International Convention Centre in Birmingham, U.K., co-hosted by RSSB and University of Birmingham.

WCRR 2022 was organized by its Organizing Committee consisting of UIC, MxV Rail (formerly TTCI) of the U.S., RSSB of the U.K., SNCF of France, DB AG of Germany, Trenitalia of Italy, and Railway Technical Research Institute of Japan, for the purpose of improving the value of railway research, sharing technical information, and promoting international cooperation.

The University of Birmingham and UNIFE (The Association of the European Rail Supply Industry) joined the Organizing Committee for this congress.

○ **Congress theme:** Reshaping our railways post-pandemic: Research with an impact

○ **Participants:** 757 people from 31 countries, 60 from Japan and 22 from RTRI

○ **Plenary sessions:**
Three plenary sessions were organized and the Organizing Committee members, railway operators (mainly from Europe), research organizations and representatives of manufacturers joined the panel discussions. Representing Japan, Executive Director Furukawa of RTRI joined Plenary Session 2 "Research with an Impact: Celebrating Success" and talked about the results of Japanese anti-seismic measures, cost reduction by introducing multi-purpose telecommunication lines to wireless train control, and research and development in Japan to decarbonize railways.

Session 1	The railway in a post-covid transport landscape
Session 2	Research with an impact: Celebrating success
Session 3	The journey to rapid benefit realization

○ **Presentations:** 168 presentations for oral sessions (10 from RTRI)
130 presentations for interactive sessions (8 from RTRI)

Executive Director Furukawa and plenary session participants

◯ **Awards:**

Nine presentations from a total of 298 were selected for best paper awards, one from each of 9 categories. From Japan, Mr. Hiroshi Yoda, Assistant Senior Researcher of RTRI received the Best Early-Career Researcher Award for his presentation "Improvement of the Wireless Power Transfer System for Railway Vehicles".

*The next WCRR will be held in 2025 in Colorado Springs or Denver in the U.S., hosted by MxV Rail.

Best Early-Career Researcher Award winner Mr. Yoda

RTRI's exhibition booth representing the JR group companies

Best Papers and award winners

Name	Organization	Category
David Thompson	University of Southampton (UK)	Low Emissions Railway
Daniel Schmeling	DLR (German Aerospace Institute) (Germany)	Easy to Use for All
Javier Goikoetxea	CAF (Spain)	Optimised Operation
Riccardo Licciardello	Sapienza University of Rome (Italy)	Reliable and Easy to Maintain Moving Assets
Bleddyn Davies	Network Rail (UK)	Reliable and Easy to Maintain Fixed Assets
Sebastian Stichel	KTH Royal Institute of Technology (Sweden)	Reliable and Easy to Maintain Asset Interfaces
Allan Armougum	SNCF(France)	Safety and Security
Giusy Elena Caci	Italferr (Italy)	Rail Competitiveness
Hiroshi Yoda	RTRI (Japan)	Best Early Career Researcher

RTRI's Researcher Receives Young Scientist Award

Dr. Munemasa Tokunaga, Senior Researcher of RTRI, received the Young Scientist Award for 2022 from the Minister of Education, Culture, Sports, Science and Technology. On May 24, Dr. Tokunaga was handed the commendation certificate by Dr. Masao Mukaidono, Chairman of RTRI.

Award winner :
Dr. Munemasa Tokunaga,
Senior Researcher, Structural Mechanics,
Railway Dynamics Division

Dr. Watanabe, President of RTRI　　Dr. Tokunaga　　Dr. Mukaidono, Chairman of RTRI

Outline of the research:

Railway systems consists of many kinds of components including vehicles, tracks, structures, and power supply facilities. So far, however, interactions between these components have not been sufficiently studied, but rather overlooked or oversimplified.

Dr. Tokunaga analyzed the mechanism of dynamic responses between bridges and railway vehicles in order to pursue bridge structures capable of withstanding intensified earthquake vibration and recent increases in train speeds. Dr. Tokunaga has particularly focused on three dynamic interactions having greater impacts: between bridges and vehicles, between bridges and noise-barriers, and between adjacent bridges. Based on the results, he has developed methods to evaluate dynamic behaviors of bridges including noise barriers and vehicles during earthquakes or during train passages and has also developed railway bridge design methods.

The result of his research is expected to enhance Japan's competitiveness in the global market of high-speed rail projects, as well as to improve safety and convenience of railways in Japan.

Comment by Dr. Tokunaga:

I am greatly honored to receive this prestigious award. I would like to express sincere thanks to many people including my supervisors and colleagues. I owe a great deal in achieving the result of this research to the kind support and precious advice by all of them, and to the wonderful research environment at RTRI.

Due to the increasing number of large-scale earthquakes and speed increase of the Shinkansen in recent years, more detailed, deeper analysis has been required to elucidate dynamic interactions between the railway system components such as railway bridges. I believe this research achievement, crossing over different fields of railway technologies, will further drive the development of railways.

Keeping in mind this honorable, encouraging moment, I would like to continue research in order to contribute to enhancing the value of railways and creating an affluent and harmonious society.

* Young Scientist Award by the Minister of Education, Culture, Sports, Science and Technology:

This award is given to outstanding young researchers under age 40 who achieve distinguished research newly-emerging issues or from unique and original perspectives.

Railway Technical Research Institute