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Special Contribution

Disaster Countermeasures and Recovery Technology for Existing Railway Structures

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1. Introduction

Huge earthquakes and localized heavy rain, which have been frequent in recent years, have caused damage to different types of social infrastructure, including railway structures. Damage to railway structures has led to disruption or suspension of operations in the past, sometimes up to several years, or relatively shorter periods, depending on the seriousness of the damage. Therefore, this report summarizes the findings obtained from damage to railway structures caused by past earthquakes and rains. In addition, it details disaster countermeasures for railway structures on which Railway Technical Research Institute (RTRI) has been working (preliminary diagnosis, reinforcement technology and technology for detecting damage in the event of a disaster) and recovery examples technically supported by the RTRI. Finally, the report discusses disaster prevention and mitigation technology for further improving railway resilience and future work on early recovery technology.

2. Characteristics and issues of past earthquake damage and rain damage

This section overviews recent earthquakes and rain disasters that damaged railway structures. Here, the 2011 off the Pacific Coast of Tohoku Earthquake and the 2016 Kumamoto Earthquakes, and as for rains, it addressed the Heavy Rain in Northern Kyushu in July 2012 and the 2016 heavy rains caused by Typhoons 7, 9, 10, and 11.

The 2011 off the Pacific Coast of Tohoku Earthquake was an unprecedented huge trench-type earthquake with a magnitude of 9.0[1]. Regarding the earthquake damage of railway structures, there was no collapse of the structures thanks to the effects of shear reinforcement measures and measures to prevent the collapse of bridges that were implemented after the Hyogo-ken Nanbu Earthquake; however, there was a characteristic damage due to a huge earthquake, including utility pole breakage over a wide area, viaduct column damage, damage caused by repeated aftershocks(Fig.1), ground liquefaction damage in the Tokyo urban area, and enormous tsunami damage in Tohoku coastal areas.

The Kumamoto Earthquakes, which were inland earthquakes, included a foreshock with a magnitude of 6.5 due to the Hinagu fault, which occurred on April 14, 2016, and the main shock with a magnitude of 7.3 due to the Futagawa fault which occurred two days later [2]. Observations revealed that the covered concrete at top of viaduct columns forming part of Kyushu's Shinkansen Structure in the plain of Kumamoto had been peeled off and that bridge bearings had been damaged. However, this was within the scope of consequences assumed in Railway Design Standards. On the other hand, many large-scale landslides occurred in mountainous areas and intermountain regions centered on the Minamiaso area, and the subsequent aftershocks occurring in succession caused damage and deformation to progress, leading to more extensive damage (Fig.2).

The Heavy Rain in Northern Kyushu in July 2012 was described by the Japan Meteorological Agency as "rain of unprecedented intensity for Japan". The total recorded rainfall was over 800 mm in three days and caused major river disasters to northern Kyushu, mainly in Kumamoto, Oita, Fukuoka, and Saga Prefectures [3]. The heavy rainfall also damaged valley fills, embankments, and river bridges, including the Hohi Main Line, which runs through the intermountain region (Fig.3).

The heavy rains in 2016 was caused by Typhoons 7, 9, 10, and 11. Three typhoons landed in Hokkaido in succession over a single week, and heavy rain caused flooding of rivers and sediment-related disasters mainly in eastern Hokkaido. Subsequently, heavy rain generated by a front at the end of August and the approach of Typhoon 10 caused great damage such as the outflow of river bridges on the Nemuro Main Line and coastal revetments on the Hidaka Main Line (Fig.4) [4].

Fig. 1. Example of damage caused by aftershocks from the 2011 off the Pacific Coast of Tohoku Earthquake

Fig. 2. Example of damage caused by the Kumamoto Earthquakes in 2016 (Minamiaso Area; assumed bridge deformation shown by yellow lines)

Fig. 3. Example of damage caused by Heavy Rain in Northern Kyushu in July 2012

Fig. 4. Example of damage caused by Typhoon 10 in 2016 (river bridge)

These examples illustrate recent natural external forces due to earthquakes or rain have become extreme. In the case of earthquakes, multiple succession of earthquake motion, including the main shock, cause initial damage to railway structures to progress and expand. In the case of rain, localized short-term heavy rain causes sudden rises in water levels, resulting in overflow exceeding the height of railway structures, which leads to extensive damage.

The performance or function of a railway structure before and after a disaster change rapidly (Fig.5). The curve declines sharply immediately after the disaster and returns to its original height of form as recovery is made. In this figure, both "the avoidance of catastrophic conditions", that is, the suppression of performance degradation, and "the early recovery of the functionality of the overall system" are defined as "resilience". To increase the railway resilience, we need to take pre-disaster action (disaster prevention and mitigation technology) and post-disaster action (judgment technology for an early train operation restart and early recovery technology) on this curve.

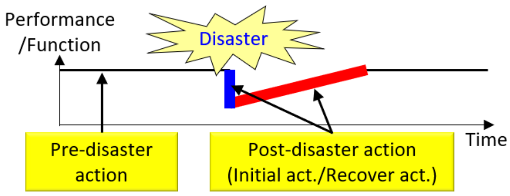

Fig.5. Performance and function of structures before and after the disaster

3. RTRI's disaster countermeasures - Pre- and Post- disaster action

For pre-disaster action, it is important to have a reinforcement technology that can extract weak points on a railway line in advance and then enables work to make them more toughness. For post-disaster action, technology that be able to facilitate detection of damage to railway structures, to determine if damage is minor immediately after a disaster, leads to rapid resumption of train operations. In the case of more serious damage, a post-disaster diagnosis to determine whether the structure is reusable by reinforcement or should be replaced, leads to implementation of reinforcement technology (Fig.6). This section describes a series of disaster countermeasures on which the RTRI has been working, including pre- and post-disaster actions (initial and recovery actions).

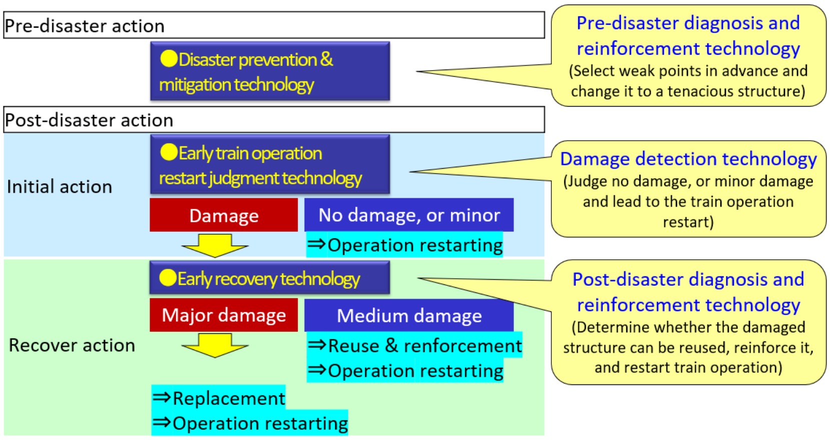

Fig.6. Railway disaster countermeasures (pre- and post-disaster actions)

3.1 Pre-disaster diagnosis and reinforcement technology

Intermountain regions and valley terrains, called catchment terrains, tend to collect groundwater, and embankments constructed in such places generally have low seismic resistance. To establish a seismic diagnostic technology that takes into account changes in soil strength caused by groundwater inflow or outflow, RTRI has developed a method which represents soil as a three-phase material consisting of soil particles, water and air, and makes it possible to perform seismic diagnosis of an embankment on a catchment terrain by continuously analyzing the seismic response from saturated / unsaturated seepage analysis considering the groundwater inflow and outflow(Fig.7)[5]. From a precipitation experiment and shaking table test in the gravitational field using a 1/10 model, we verified that a series of saturated / unsaturated seepage analyses and seismic response analyses were able to precisely express the two experimental results of the embankment model with an impermeable layer and the embankment model without an impermeable layer.

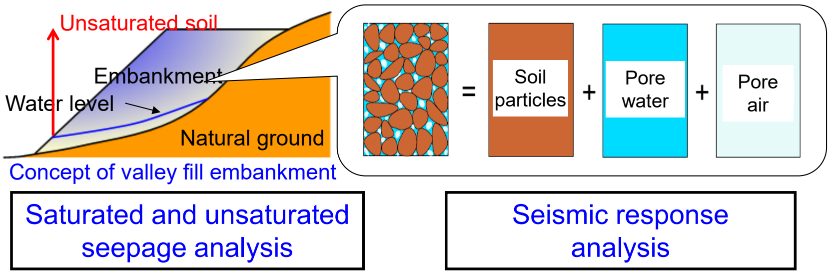

Fig.7. Seismic diagnosis of embankment on the catchment terrain

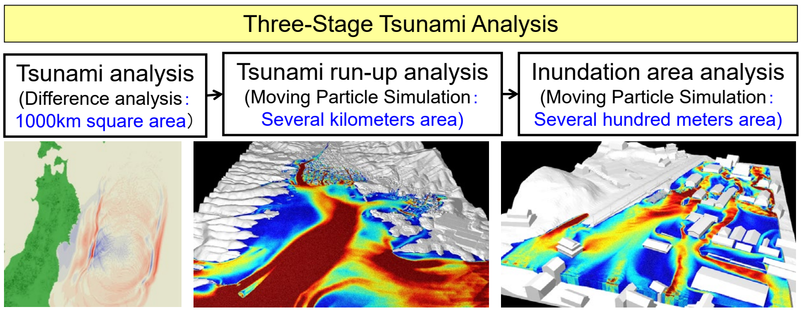

Fig.8. Three-Stage Tsunami Analysis with the difference analysis and moving particle simulation methods

Damage caused by tsunamis may be unprecedented or extremely rare depending on the area. However, should one occur, damage is likely to be huge. By combining the difference analysis and the moving particle simulation (MPS) method, RTRI developed a Three-Stage Tsunami Analysis that can estimate the occurrence of a large-scale tsunami, tsunami run-up, and then the inundation area while taking in outflows (i.e. with floating matters) (Fig.8) [6]. By reducing the analysis area at each stage and matching the inflow and outflow of each boundary condition, the calculation time can be shortened while performing a more detailed analysis. The occurrence of the tsunami was analyzed using a two-dimensional difference method from the assumed fault displacement of the 2011 off the Pacific Coast of Tohoku Earthquake (1000km square); next, the run-up of the tsunami in Kesennuma Bay was analyzed by the three-dimensional moving particle simulation method (4km×2km); finally, the inundation area of the tsunami near Shishiorikarakuwa Station on the Ofunato Line was analyzed by the three-dimensional moving particle simulation method (180m×150m). Based on the result of the first step in the tsunami analysis, the run-up analysis of the tsunami in Kesennuma Bay in the second step, and the inundation analysis of the tsunami near Shishiorikarakuwa Station in the third step, it was verified that we can almost trace the measured values of the tsunami height due to the 2011 off the Pacific Coast of Tohoku Earthquake, the observed values of the inundated area, and the actual damage.

For the purpose of making steel girders / abutment type bridges earthquake-resistant without rebuilding the bridges, we proposed an integrated method using steel girder, abutments and backfills by connecting the abutment and the backfill with nail-reinforced members, forming a rigid-frame structure by RC rolling up of the steel girder and the abutment, that is, Integrated Bridge with Nail-Reinforced Soils(Fig.9). It is an epoch-making construction method that aims to improve the function by changing the steel girder / abutment / embankment boundary, which was a weak point in the boundary of the structure, to a continuous structure [7]: it can also let to increase the outflow resistance of steel girders against river-bridge overflow.

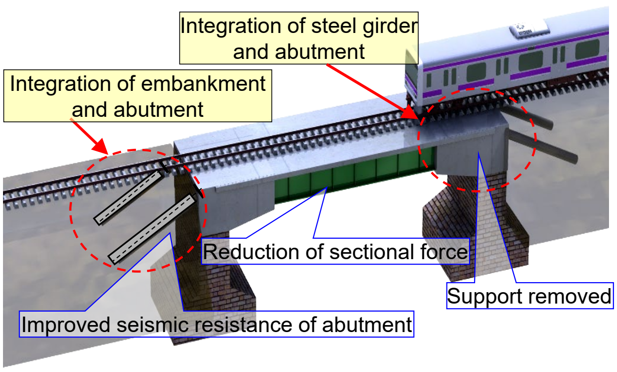

Fig.9. Integrated structural method of steel girder, abutments and backfills (Integral bridge with nail-reinforced soils)

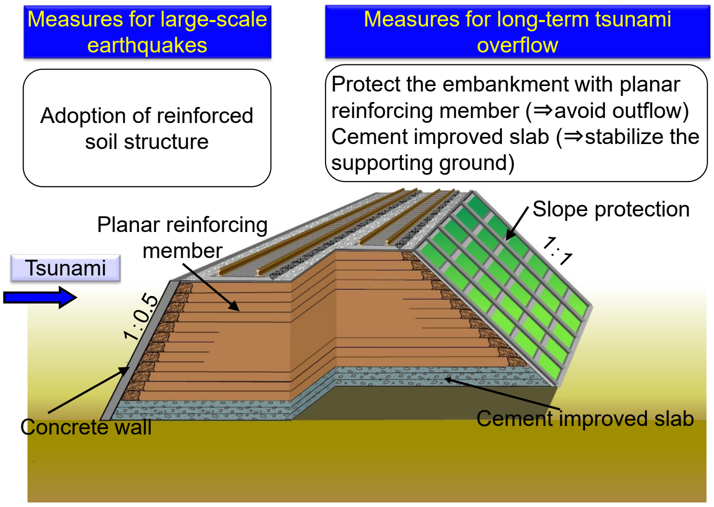

Fig.10. Embankment structure for tsunami and resistance

As a technology to prevent the outflow of embankments due to tsunamis, we proposed an embankment structure using a geosynthetic reinforced soil structure and cement-improved slab (Fig.10) [8]. These structures are intended to prevent an outflow of soil particles by planar geosynthetic reinforcing and to stabilize the embankment by cement improved slabs against a tsunami overflow that continues over a long period of time. As a result of our overflow experiment using the conventional 1/10 embankment model and an embankment model of the proposed structures, the conventional embankment exhibited an eroded slope and sudden downward flow, resulting in progress and expansion of the scouring. With the new proposed structure, no erosion occurred on the embankment and the embankment remained stable, although the supporting ground on the back surface was scoured. The same concepts as the proposed structure were applied to the tsunami countermeasures for the existing embankment: to install a nail-reinforced member, slope protection to prevent the outflow of soil particles, and an enclosing method using steel sheet piles to prevent scouring of the supporting ground.

3.2 Post-disaster diagnosis and reinforcement technology

Once a railway structure is damaged, diagnosis of the damaged structure and reinforcement are required. This subsection introduces the technical supports provided by RTRI for recovery after the disaster caused by Heavy Rain in Northern Kyushu in July 2012, and after the 2016 Kumamoto Earthquakes.

Following the Heavy Rain in Northern Kyushu in July 2012, at the Kumanoue River Bridge on the Kyudai Main Line, the supporting ground on the foundation bottom surface was sucked out and scoured due to flooding, and the P2 pier sank about 350 mm. Although the soundness diagnostic test for viaduct pier “Impact Vibration Test” conducted after the disaster confirmed that the pier was less sound, the existing girders and pier were deemed to be reusable based on a loading test, etc.. Train operations were able to restart after eliminating looseness in the supporting ground, and after completing loading tests. Specifically, a vertical loading test with a water tank (loading up to 90% of locomotive load DE10) showed convergence of settlement, and a locomotive running test, including a train stop test that applied braking load, demonstrated that the settlement had almost converged. A series of these loading tests led to the train operations being able to restart about one month after the disaster. The foundations were reinforced with Sheet Pile Reinforcement Method, and then speed restrictions were lifted in April 2013(Fig.11).

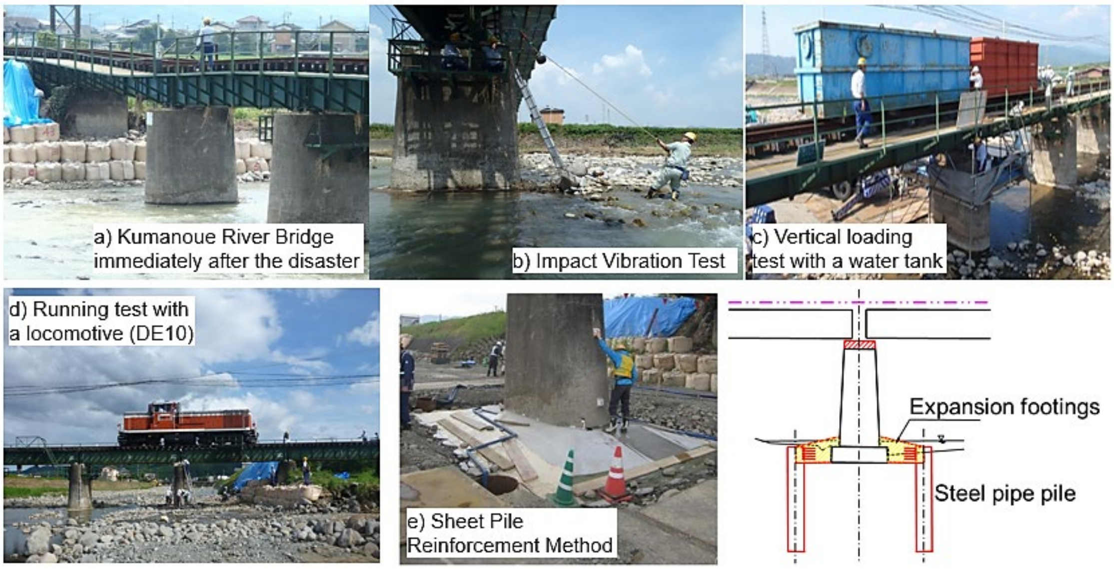

Fig.11. Technical support for diagnosis and reinforcement of the Kumanoue River bridge damaged by Heavy Rain in Northern Kyushu in July 2012

Fig.12. Technical support for the diagnosis of the Kyushu Shinkansen viaduct damaged by the Kumamoto Earthquakes in 2016

The Kumamoto Earthquakes damaged the rigid-frame viaduct columns and bridge bearings on the Shin-Tamana to Shin-Yatsushiro section of the Kyushu Shinkansen line. There were well over 1000 columns and bearings, and there was concern that it would take a long time to investigate each damaged location, formulate a recovery plan, and then carry out repairs. As such, a strategy was adopted, where recovery would be achieved step-by-step: damaged sections would be ranked by degree of damage, and based on an index of whether they needed to be repaired or not prior to resumption of train operations. Operations would then be resumed with speed restrictions, which could then be gradually lifted. As a result, train operations restarted on the Hakata-Kumamoto section on April 23, 2016 (9 days after the disaster) and restarted on all the Kyushu Shinkansen lines on April 27(Fig.12).

In both cases, early recovery was achieved by diagnosing the railway structures following the disaster and by repairing and reinforcing them based on these diagnoses. The case of the Kumamoto Earthquakes was the first example where a large number of damaged locations in a wide area were classified based on severity of damage, and divided into sections in the recovery plan, so that speed restrictions could be lifted progressively for each section after train operations resumed.

4. Toward further improvement of resilience

This section describes future work which will aim to further improve railway resilience.
Flood or tsunamis are accompanied by infiltrations, overflow, erosion (scouring), sedimentation, and outflow (of driftwood, piers, girders, etc.), which exhibit complex phenomenon caused by flowing water. For the effects of these infiltrations, erosion (scouring), sedimentation and outflows, the damage caused by floods or tsunamis can become widespread and serious. For example, the Heavy Rain in Northern Kyushu in July 2017 generated large amounts of driftwood and landslide outflows which extended the damage. There is the lack of data on similar events, and then this means to unprecedent in past time. Forecasting possible damage and extracting vulnerable points are more important in such an inexperienced event. In addition, also as for recovery, expanded and more enormous damage being caused by a flood or tsunami in future is no choice but to deny the concept of unreinforced recovery.

By estimating the tsunami inundation area and damage by the Three-Stage Tsunami Analysis, flowing water, suspended matter, and structures were expressed, but deformation or destruction of a structure such as an embankment or bridge were not expressed in present. When a flood or tsunami occurs, outflows are mixed in addition to water, soil and structures, and the flow will change due to the interaction among these. At that time, the deformation and destruction of soil and structures progressed due to flowing water, infiltration, erosion (scouring) and sedimentation, lead to more extensive damage (Fig.13). Thus, in the estimation of the damage caused by an unprecedented flood or tsunami, the existing three-stage tsunami analysis is considered to be required to develop a large-scale deformation / destruction analysis in consideration of infiltration, erosion(scouring), sedimentation, deformation / destruction, and outflow of structures (embankments and bridges): and there is demand for such analysis methods. Developing a large-scale destruction analysis of soil and structures accompanied by erosion(scouring) and sedimentation with flood is an advanced research and development subject, which is also difficult at an academic level.

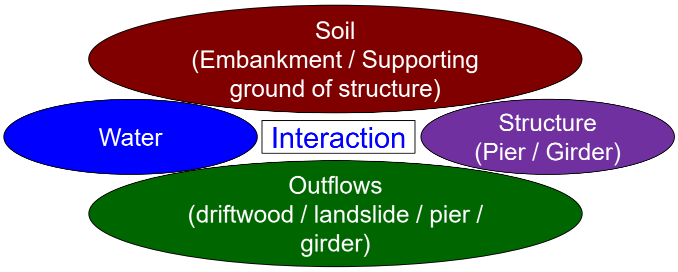

Fig.13. Interaction between water, soil, structures, and outflows during flood or tsunami

In the case of structures damaged by floods, earthquakes, or tsunamis, we must also consider shifting our approach from unreinforced recovery to reinforced recovery. As such, this demands step-by-step reinforced recovery technologies, which enable step-by-step reinforcement to allow early resumption of train operations and avoid catastrophic damage to railway structures in the event of a new disaster (Fig.14). Consequently, there is also demand for a step-by-step reinforced recovery technology applicable to a range of structures that can be easily implemented for early recovery and for reinforced recovery.

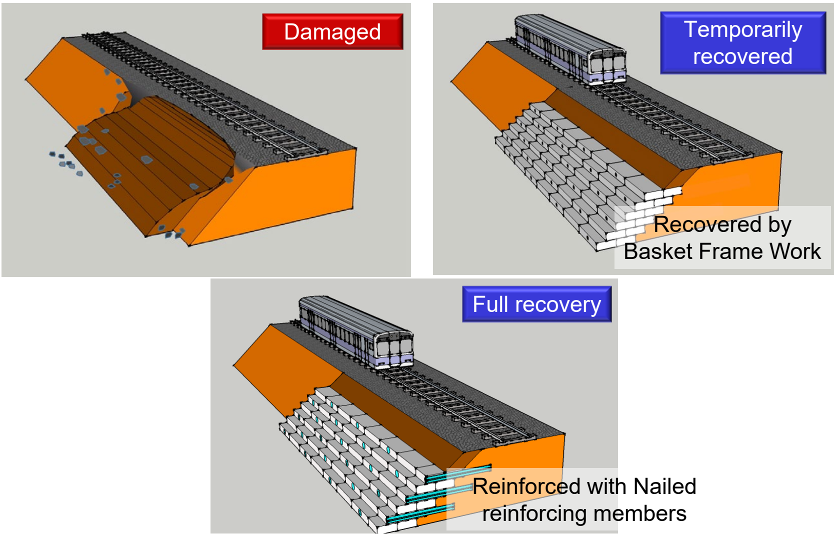

Fig.14. Example of step-by-step reinforced recovery of a damaged embankment

5. Conclusions

This report gave an overview of findings obtained about damage to railway structures caused by past earthquakes and heavy rain. Then, the pre-disaster action and post-disaster action on which RTRI has been working, with a special focus on disaster countermeasures of railway structures for the purpose of improving the railway resilience, were introduced. The followings were obtained from the discussions.

Since infiltration, erosion(scouring), sedimentation and outflows exacerbate damage caused by flood or tsunamis, the simulation technology in the pre-disaster action to estimate accurately a wide-area disaster, and the step-by-step recovery technology in post-disaster action would further improve the railway resilience. The RTRI will continue the research and development that contributes to improving railway resilience, aiming for practical development.

The integrated structural method of steel girder, abutment and embankment presented in the text, was implemented with the support of subsidies for railway technology development from the Ministry of Land, Infrastructure, Transport and Tourism.

REFERENCES

[1] Tateyama, M., “Earthquake-resistant technology for railway facilities,” Summary on the 24th Railway Technical Research Institute Lectures, 2011.11 (in Japanese).
[2] Japanese Geotechnical Society, “Report on 2016 Kumamoto Earthquake Disaster related to soils and foundations,” 2017.4 (in Japanese).
[3] Investigation teams on Heavy Rain Disaster in Northern Kyushu in July 2012, Japan Society of Civil Engineers, “Report on Heavy Rain Disaster in Northern Kyushu in July 2012,” 2013.2 (in Japanese).
[4] Investigation teams on heavy rain disaster in Hokkaido in August 2016 related to soils and foundations, Japanese Geotechnical Society, “Report on Heavy Rain Disaster in Hokkaido in August 2016,” 2017.8 (in Japanese).
[5] Matsumaru, T., Kojima, K., & Tateyama, M., “Fundamental research about seismic behavior of embankments affected by seepage water,” JSCE Journal, C (Geosphere Engineering), Vol.70, No.1, pp.135-149, 2014 (in Japanese).
[6] Murotani, K., Takagaki, M., “Structural analysis of railway structures using the MPS method by tsunami wave pressure,” presented at the 22nd Computational Engineering Lectures, at Sonic City (Saitama City, Saitama Prefecture), 2017. (in Japanese).
[7] Koda, M., Nonaka, T., Tateyama, M., Tatsuoka, F., “Earthquake resistance of structural boundaries between bridges and backfills -Integral bridges with nail-reinforced soils-, Bridges and Foundations, Vol.47, No.12, pp.22-27, 2013.12 (in Japanese).
[8] Watanabe, K., Matsuura, K., Nonaka, T., Fujii, K., Kudo, A., Nakajima, S., “Geosynthetics reinforced soil that persistently resists large earthquakes and tsunami overflows,” Journal of Geosynthesis, Vol.64, No.3, pp .8-11, 2016 (in Japanese).

◆ A brief CV of Dr. Masayuki Koda

Masayuki Koda is the Director of Structures Technology Division, Railway Technical Research Institute in Japan (RTRI), also holds the Head of Foundation & Geotechnical Engineering Laboratory. After completing the master’s degree from Tokyo Institute of Technology (TITech) in 1993, he joined RTRI. In 1995, he moved to the post of researcher associate at department of civil engineering in TITech for three years temporally. In 1999, he came back to RTRI and received the doctor in engineering from TITech in 2000 for the thesis of “Study on Lateral Resistance of Single Pile in Sandy Ground”. He has worked on R&D for foundation engineering of railway structures, and for geotechnical engineering. He is a code writer for the series of Design Standard for Railway Structures in Japan. He is also one of the developers of the newly foundation with multiple sheet piles, “Sheet Pile Foundation, and Sheet Pile Reinforced Structure Method for existing foundations”. He is one of Directors of International Press-in Association.