Preparing for Major Earthquakes

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Introduction

To assure reliable transport railway operators must always be prepared for natural disasters. The Great East Japan Earthquake on 11 March 2011 and subsequent tsunami caused huge damage. Although the earthquake was Richter Magnitude 9.0, there were no railway related casualties and damage to railway structures from the earthquake itself was relatively minimal. Structural damage was light due to the lessons learned from the 1995 Great Hanshin Earthquake and 2004 Mid Niigata Prefecture Earthquake. However, there are still issues remaining in dealing with large earthquakes. This article explains efforts by the Railway Technical Research Institute (RTRI) to minimize damage caused by large earthquakes in the future.

Characteristics of Earthquake Damage and Lessons from Past Earthquakes

The large earthquakes that strike Japan have damaged railways in the past. Damage to embankments was recorded after the Great Kanto Earthquake (1923), Tonankai Earthquake (1944), and Fukui Earthquake (1948). Liquefaction was reported in the Niigata Earthquake (1964) and Tokachioki Earthquake (1968). As railway speeds increased systematic research on aseismic countermeasures for embankments and concrete structures started in earnest. However, the viaducts of the as-then-unopened Tohoku Shinkansen were damaged by the Miyagiken-oki Earthquake (1978), and there was still major damage when viaducts collapsed in the Great Hanshin Earthquake (1995)(Figure 1). In the Mid Niigata Prefecture Earthquake, a tunnel roadbed suffered upheaval, viaducts were damaged, and a shinkansen derailed. Although damage differs depending on whether the epicentre is in an ocean trench or inland, every possible type of damage must be covered if railways are to assure safety.

In the recent Great East Japan Earthquake, the main damage to railway infrastructure included shattered viaduct

Figure 1 Minimizing Damage to Railways from Mega-earthquakes

What should we learn from past earthquakes?

Great Hanshin Earthquake (1995)

Mid Niigata Prefecture Earthquake (2004)

Figure 2 Damage from Great East Japan Earthquake 2011

The Great East Japan Earthquake typically caused broken poles and cracked viaduct supports with some ground liquefaction at stations. Despite the size of the earthquake, the damage was not as bad as expected although coastal lines were hard hit by the tsunami.

columns, secondary damage from aftershocks, collapsed and broken electric poles, bridge girders and embankments washed away in the ensuing tsunami, damage to stations, and liquefaction under foundations (Figure 2). Excluding the tsunami damage, the main earthquake shock did not cause catastrophic damage such as viaduct collapses as occurred in the Great Hanshin Earthquake because countermeasures to shear failure of columns and bridge collapse had been taken following that disaster.

Characteristics of Great East Japan Earthquake Seismic Waves

The Great East Japan Earthquake epicentre was in an offshore ocean trench and three large plate movements along a 500-km (Figure 3) plate edge caused an enormous tsunami. Figure 4 shows the seismic acceleration and frequency spectrum at two selected locations. Data from the Great Hanshin Earthquake and Mid Niigata Prefecture Earthquake are given for comparison. There were more than two acceleration peaks and the continuous shaking

Figure 3 Broad Fault Slip Caused by 2011 Earthquake

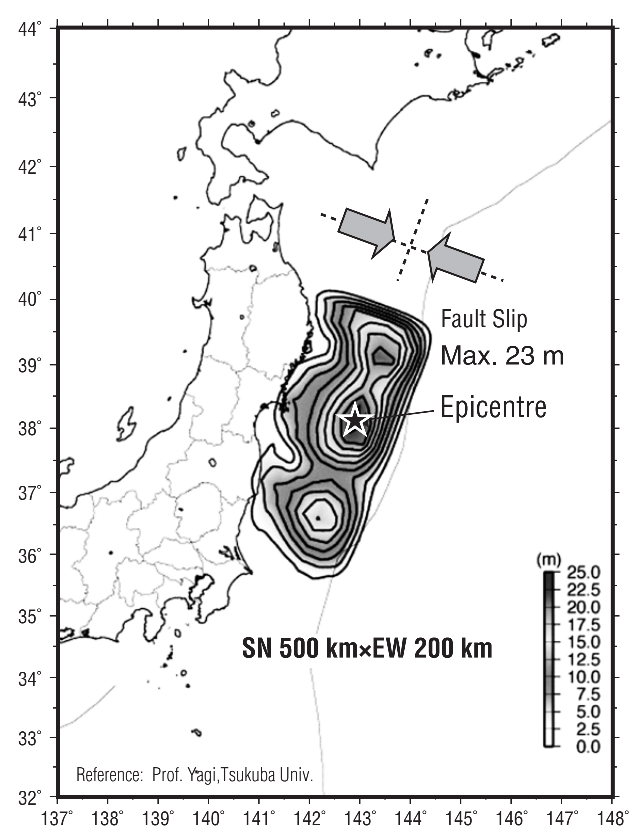
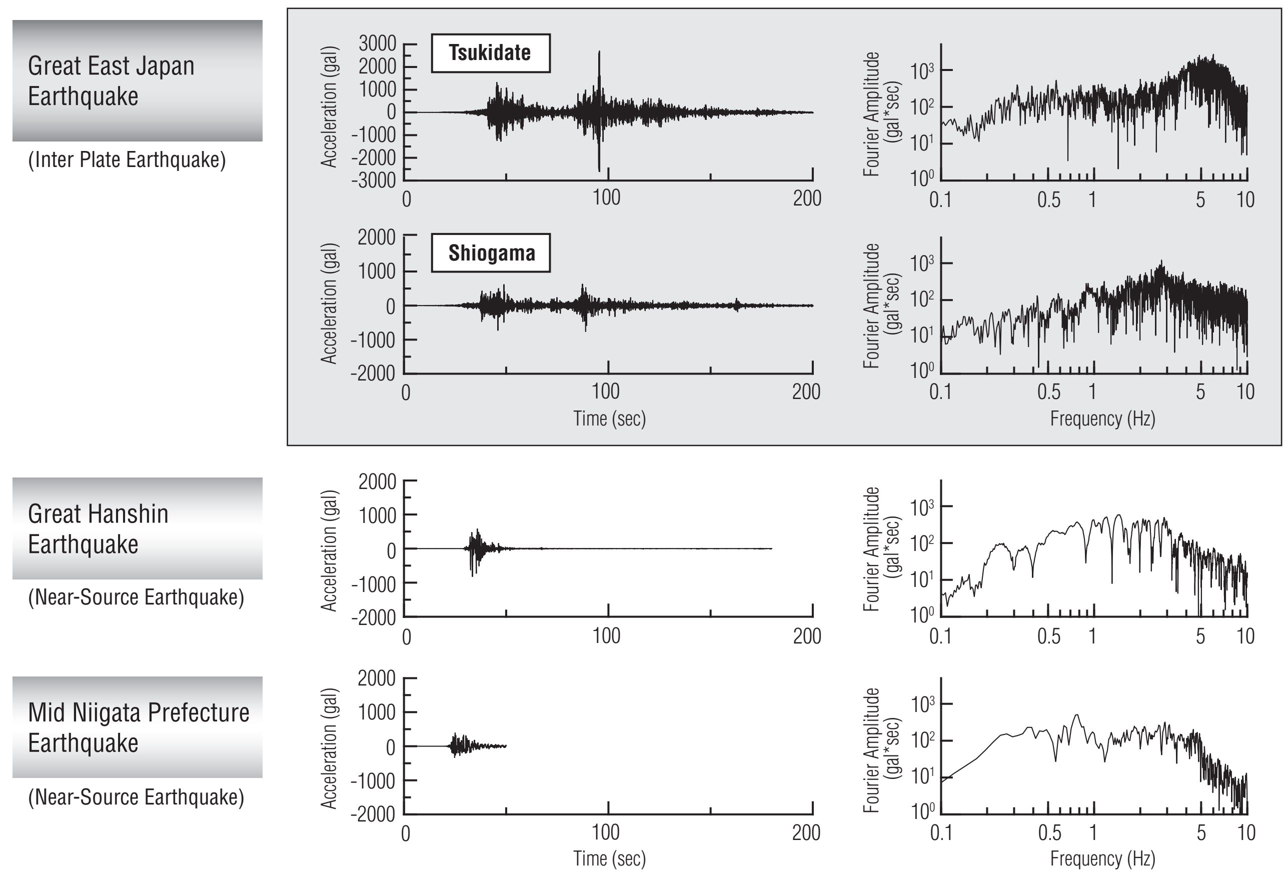


Figure 4 Characteristics of Great East Japan Earthquake

This earthquake had a long continuation time and large acceleration compared to past quakes



lasted more than 3 minutes. Compared to the other two earthquakes, the acceleration was large and the peak frequency was high at about 5 Hz, which was very different from the natural frequency of railway viaducts (2 Hz) and possibly explains why damage to viaducts was minimal.

Resisting Large Earthquakes and Tsunami

Research and development on how to resist damage from large earthquakes is split into three fields: aseismic design countermeasures; securing safe running; and early detection. Countermeasures aim to improve earthquake resistance so structures are not destroyed. Securing safe running characterizes train behaviour in an earthquake to prevent derailing. Early Detection and Warning System slows and stops trains before the main shock strikes. These are represented in Figure 5.

Improving Structural Seismic Resistance

RTRI summarized the various aseismic technologies in the form of a technical proposal in December 2011 to support restoration and recovery of railways damaged by the Great East Japan Earthquake. Figure 6 shows the technologies for regions hit by the tsunami. Figure 7 shows technologies to make existing railway facilities more earthquake resistant. There are more than eight aseismic technologies depending on the structure and location of installations, including viaducts, embankments, bridges, and stations. The technical proposal also considers how to reduce construction costs and time.

Seismic Resistance of Bridges and Embankments

The weak points of bridges in earthquakes and tsunamis are the bridge girder supports and the embankments, which are easily swept away. The geosynthetic-reinforced soil (GRS) integral bridge overcomes these weaknesses by bonding bridge girders, facings, and embankments into a single structure using concrete (Figure 8). These structures have double the seismic resistance of conventional structures.

Conventional embankments have low resistance to shaking, erosion, and flooding in large earthquakes and tsunamis. Moreover, large soil volumes are needed to build high seawalls. To overcome these problems, RTRI developed the Reinforced Railroad/Road with Rigid Facing (RRR) construction method in which reinforcing material is layered in the embankment and covered by a nearly vertical concrete facing as shown in Figure 9. Such structures remained undamaged in the Great Hanshin Earthquake. The method could be applied to seawalls, and we plan to verify its resistance to large tsunamis in the future.

Figure 5 Countermeaures to Mega-quakes

1. Aseismic Structural Design
- Anticipating seismic motion
- Anticipating responses of structures and tracks
- Improving seismic performance of structures

2. Securing Safe Running
- Anticipating behavior of running trains during earthquakes
- Preventing derailment

3. Early Detection & Warning System
- Stop operation by using Early Earthquake Detection and Warning System

Figure 6 Reconstruction Methods in Tsunami-hit Areas

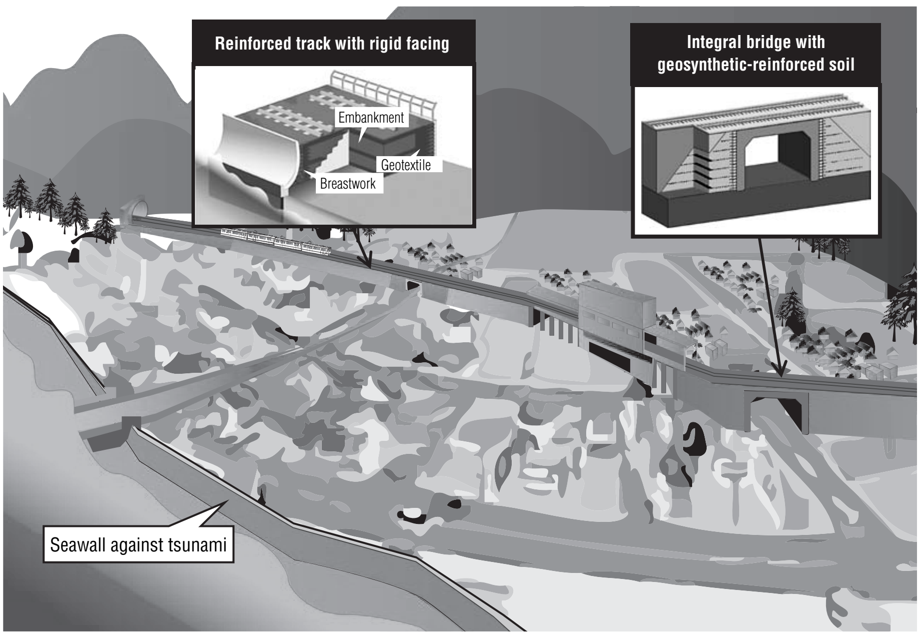


Figure 7 Aseismic Reinforcement of Existing Structures

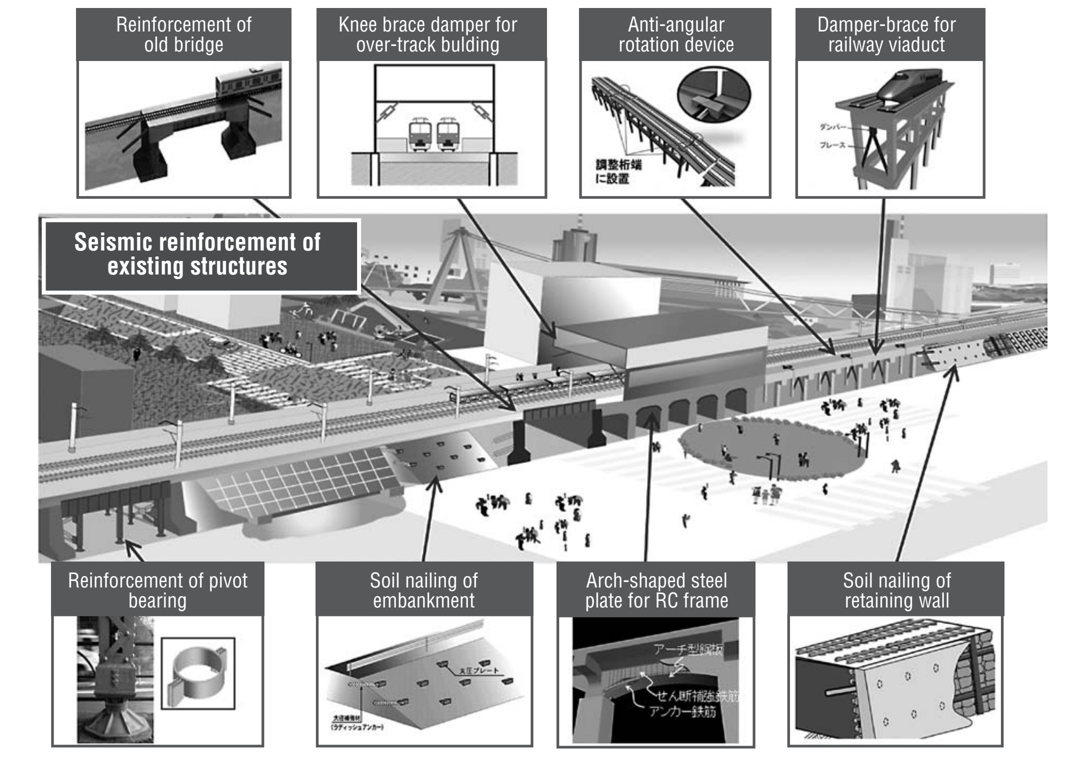
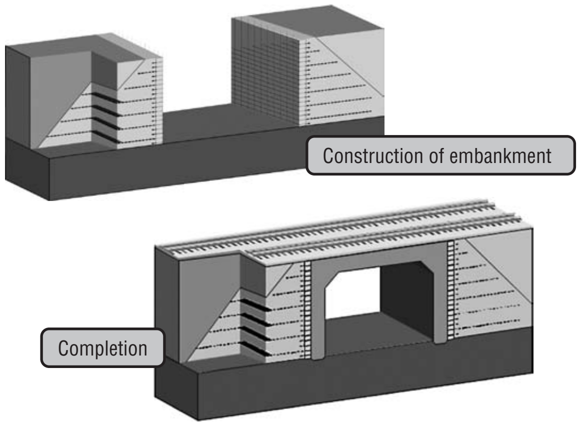


Figure 8 Construction Process and Experimental Bridge

In the integral bridge with geosynthetic-reinforced soil (RRR-GRS), the bridge frame is built after the embankment is constructed.



Experimental bridge at RTRI

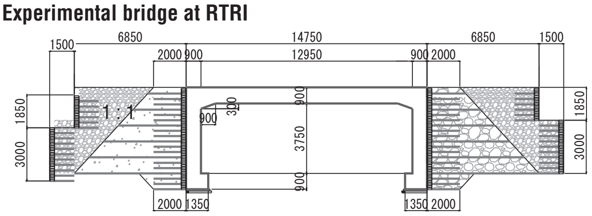
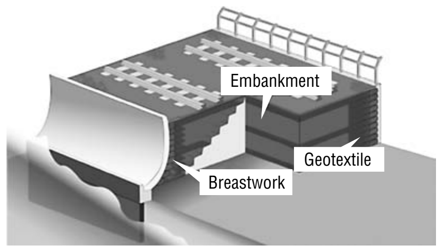


Figure 9 Reinforced Soil Wall and Application for Seawall

The Reinforced Railroad with Rigid Facing-Method (RRR) has proven high seismic performance in the Great Hanshin Earthquake. In 2011, RRR was used for reconstruction of damaged sea walls.



JR Kobe line affected by Great Hanshin Earthquake in 1995

This sea wall was damaged by a typhoon in July 2007.

Figure 10 Fundamental Behaviour of Vehicle at Rocking Derailment

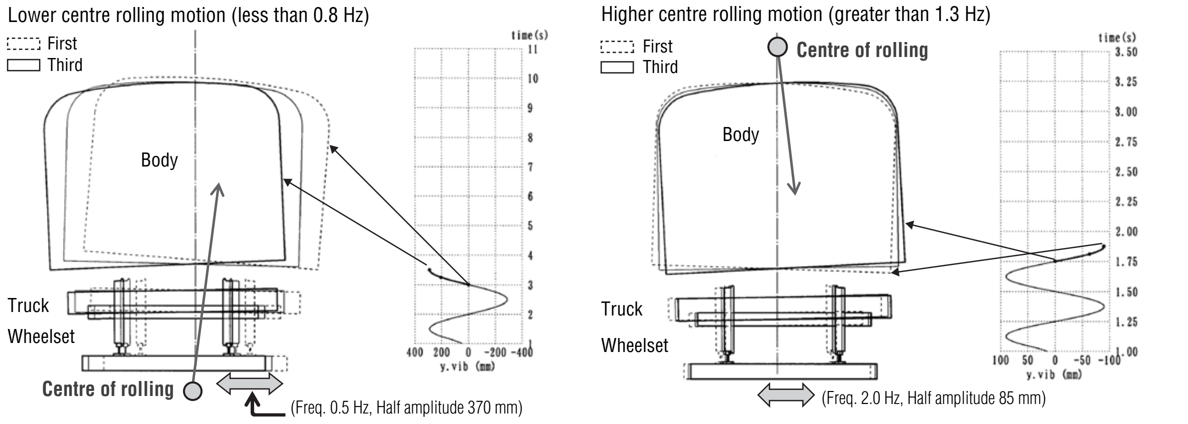
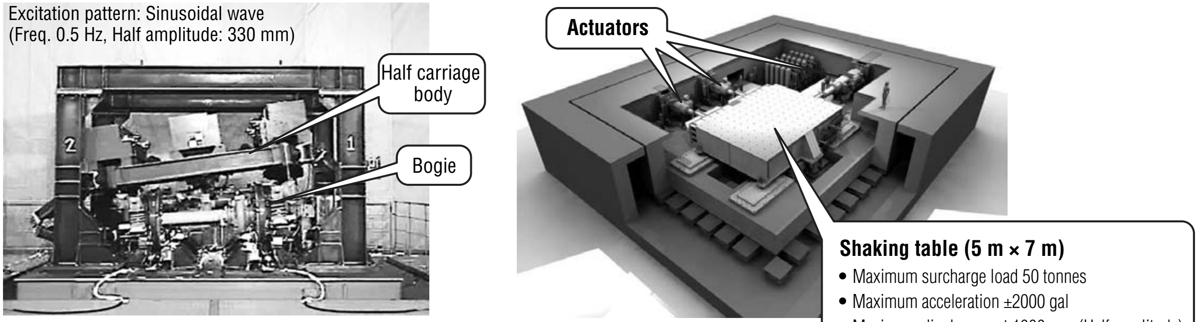
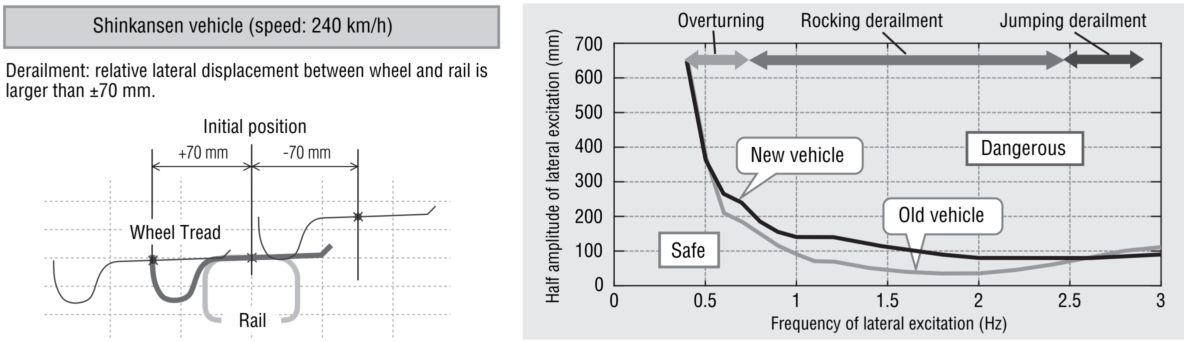


Figure 11 Vibration Test using Shinkansen Bogie (Large-scale Vibration Test Machine)



This test machine was financially supported in part by the Ministry of Land, Infrastructure, Transport and Tourism.

Figure 12 Examples of Running Safety Limit Based on Results of Vehicle Dynamics Simulation



Shinkansen Behaviour in Earthquakes

To prevent trains derailing and injuring passengers, RTRI has analyzed the detailed behaviour of rolling stock during seismic motion. We rely mostly on numerical simulations to analyze vehicle dynamics and then perform vibration experiments on shinkansen bogies to validate the simulations. Moreover, we have evaluated the running safety of specific rolling stock types to propose measures to make them harder to derail when running at high speed.

When performing numerical analysis of vehicle dynamics, it is important to perform detailed analysis of the varying dynamics of vehicles and to accurately calculate the vibration of viaducts and tracks. We have shown that seismic vibration is amplified when propagating from the ground to tracks on viaducts. We have also been able to model the jumping movement of wheels on vibrating rails.

Seismic derailment is very different from climbing-wheel derailment. In shinkansen carriages, the wheels and body roll in phase and sway gently when the lateral vibration

Figure 13 Examples of Anti-deviation Facilities after Derailment (JR East)

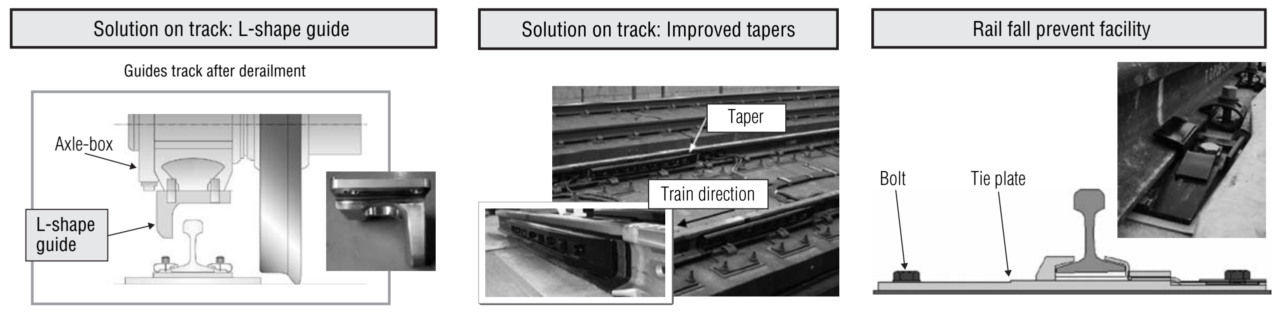
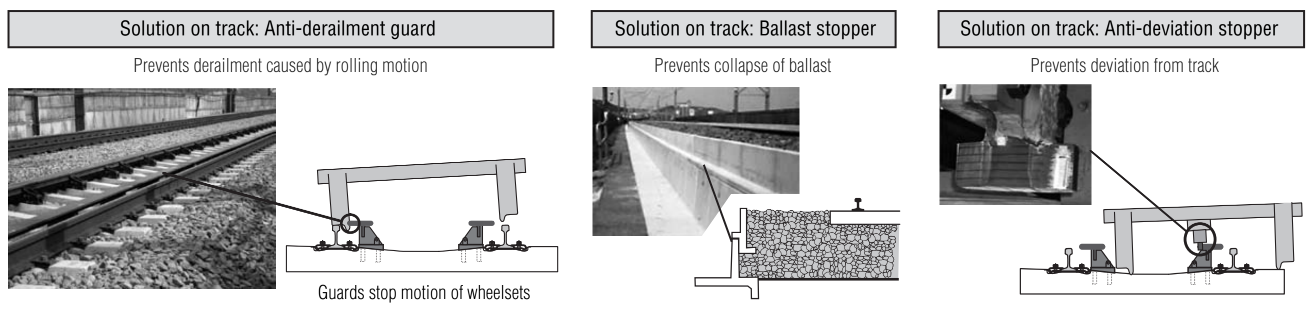


Figure 14 Examples of Anti-derailment Facilities (JR Central)



frequency of rails is about 0.8 Hz or less. However, when the lateral vibration frequency of rails is about 1.3 Hz or more, the wheels and the body roll out of phase and sway violently. In this situation, the wheel flanges and rails impact violently. Derailment is called rocking derailment when these disturbances occur in combination caused by complex waves including many frequency components (Figure 10).

To improve simulation accuracy, we shook an actual shinkansen bogie in the parallel direction to the sleepers under a load equivalent to that of a train body (Figure 11) using a vibration tester with a maximum load of 50 tonnes, maximum excitation stroke of 1 m, and maximum vibration acceleration of 2000 gal.

Running Safety Boundary Diagrams

One reason for simulating derailments is to create running safety boundary diagrams (Figure 12) by plotting rail vibration amplitudes for vibration frequencies of 0.3 to 3 Hz just before a carriage derails. The diagrams help identify basic vehicle running safety versus seismic motion and can compare the effects of different vehicle characteristics and running conditions on running performance. In Figure 12, the two lines show the running safety boundaries for two types of shinkansen rolling stock. The area under the lines is where derailment does not occur. The area above is where the probability of derailment is high. The lower area is broader for new rolling stock models than for older models, indicating the better safety of new models. However, these diagrams do not account for misalignment at boundaries of structures and bend angle.

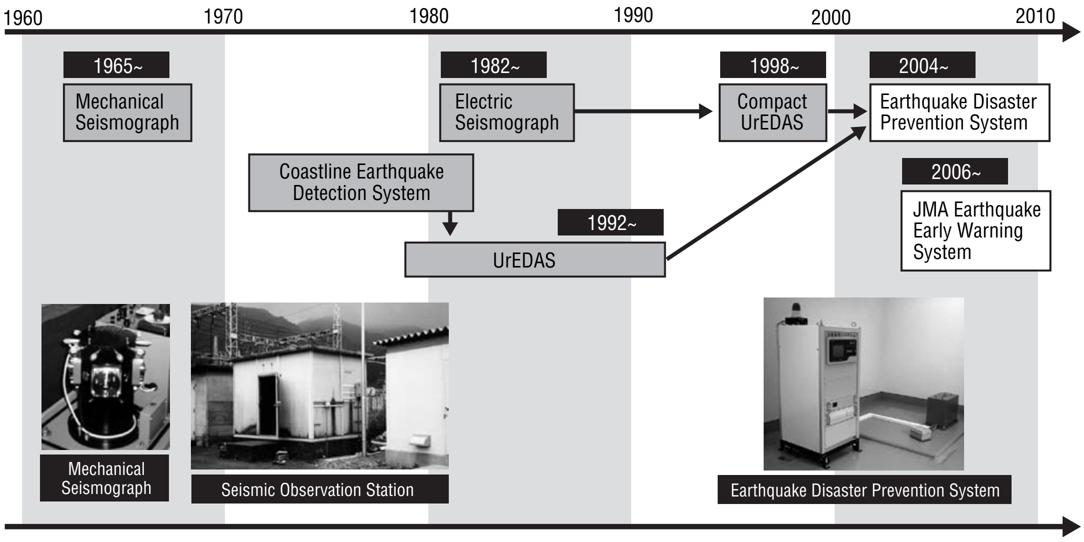
Technical Measures to Secure Safe Running

JR Companies, RTRI, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and other participants have held study meetings, the Council for anti-derailment measures for shinkansen, to propose countermeasures to shinkansen derailment since the Mid Niigata Prefecture Earthquake. The measures include adjustment of vehicle springs, dampers, and stoppers along with installation of new derailment prevention guards. In the event that carriages do derail, a method has been proposed to prevent them deviating greatly from the rails. Simulations and experiments were conducted on each of these measures, and railway operators have selected specific measures based on consideration of improvements to safety. JR East adopted a measure to prevent carriage deviation by combining L-shaped guides and rail overturn prevention devices (Figure 13). JR Central adopted a measure combining derailment prevention guards and deviation prevention stoppers (Figure 14). The two companies adopted different measures due to structural differences where one has tracks

Figure 15 Simulation of Train Motion on Railway Long-Span Bridges during Earthquake

Seismic wave of Mid Niigata Prefecture Earthquake applied to viaducts and bridges

Figure 16 Earthquake Disaster Prevention System



with many slab roadbeds and viaducts while the other has tracks with many ballasted sections and embankments.

Effects of General Simulation

To assess the safety of shinkansen rolling stock running on various structures, previous actual seismic vibrations are used as simulation input waves. For example, inputting the ground seismic waves observed during the Mid Niigata Prefecture Earthquake recreated the behaviour when the shinkansen derailed (Figure 15). In this test, the rolling stock behaviour included numerical simulation of the effects of rail angular bending at structural boundaries. At large-scale seismic motion, general simulation to analyze the behaviour of wayside equipment from the ground to the track surface and the behaviour of the rolling stock is very effective in setting and assessing measures to secure safe running.

Development and Introduction of New Early Warning Seismometers

Trains must decelerate and stop quickly in an earthquake to prevent damage. Following the 1964 opening of the Tokaido Shinkansen, systems were equipped with seismometers in 1965 to stop trains in an earthquake (Figure 16). As shinkansen speeds increased, RTRI developed the Urgent Earthquake Detection and Alarm System (UrEDAS) using the first early P-wave vibrations to quickly estimate the earthquake epicentre and magnitude, evaluate the expected size of the main shock (S-waves), and stop trains. A newer earthquake early warning system was developed in 2004 reducing the time to estimate the distance from the epicentre and the magnitude and giving more time to stop the trains (Figure 17). Today, more than 180 seismometers of the new system are installed along coasts and railway lines across Japan.

Figure 17 Principle of P-wave Warning

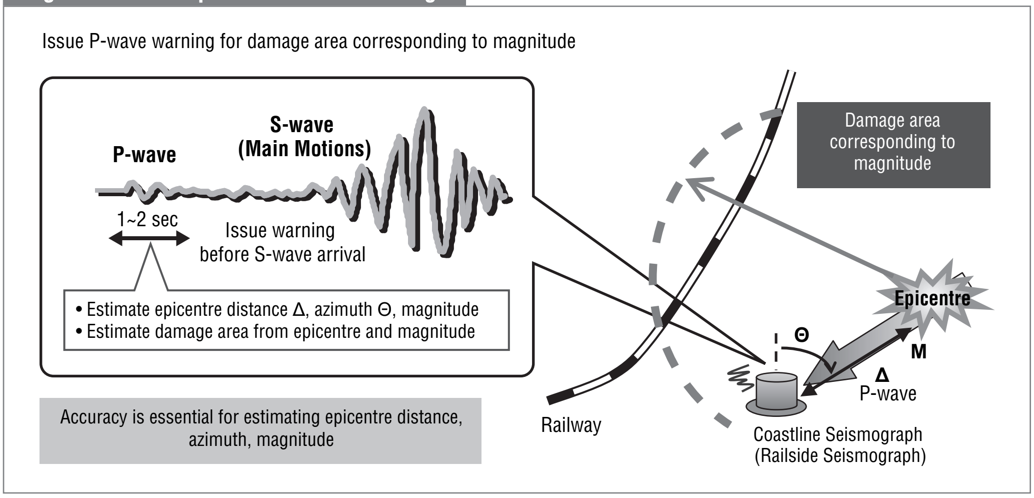
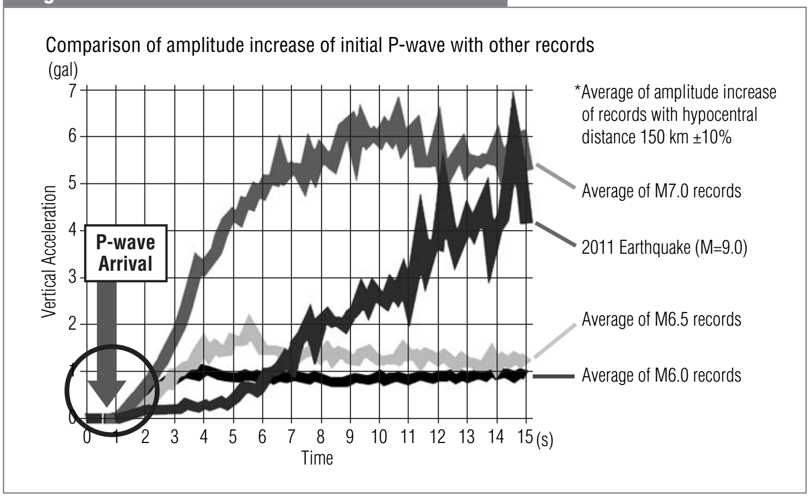


Figure 18 Characteristics of P-wave Motion



Characteristics of 2011 Earthquake and P-wave Warning Detection

In the Great East Japan Earthquake, the P-waves and S-waves were detected almost simultaneously, which means that the P-wave early warning was not very effective. To clarify the characteristics of these seismic waves, the average values for seismic waves from past earthquakes at almost the same distance from the epicentre were compared with the 2011 earthquake (Figure 18). The start of the P-wave acceleration in 2011 was much gentler than past earthquakes. At present, we do not know if this phenomenon is unique to very large earthquakes. However, if the P-wave acceleration is gentle, the magnitude is underestimated. We are now beginning to study better methods for quickly estimating earthquake parameters.

Future Efforts

Japanese railways and railway researchers have developed earthquake countermeasures based on past earthquakes. These measures seem to have proved effective against the recent giant Great East Japan Earthquake. However, some previous measures were inadequate and new issues came to light.

In countering tsunami, we especially need methods for assessing hardware enhancements as well as measures for guiding people to safety before the tsunami arrives. Methods for assessing damaged railway structures are also needed.

Placement of seabed seismometers in addition to shoreline seismometers might be effective for earlier earthquake detection. But further risk-management techniques including risk assessment methods must be developed to conduct measures in a prioritized and effective manner. ■

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Dr. Norimichi KUMAGAI is a Vice President of Railway Technical Research Institute. He Joined JNR in 1976 and worked on planning of new rolling stock. In 1987 he joined RTRI as a General Manager of Brake Control Laboratory and High-Speed Rail Project. He was consecutively Executive Director in charge of R&D, and Vice President. He earned his PhD degree in Tohoku University in 2004.