Technological Development for the Tokaido Shinkansen: Recent Efforts in Countermeasures against Earthquakes

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Introduction

The Tokaido Shinkansen opened in 1964 as the world's first high-speed railway. It is a key transport artery connecting Tokyo, Nagoya, and Osaka and it has evolved into a sophisticated, high-speed railway by refining service in areas such as safety, punctuality, convenience, ride comfort, and environmental friendliness. The evolution was supported by various technological developments.

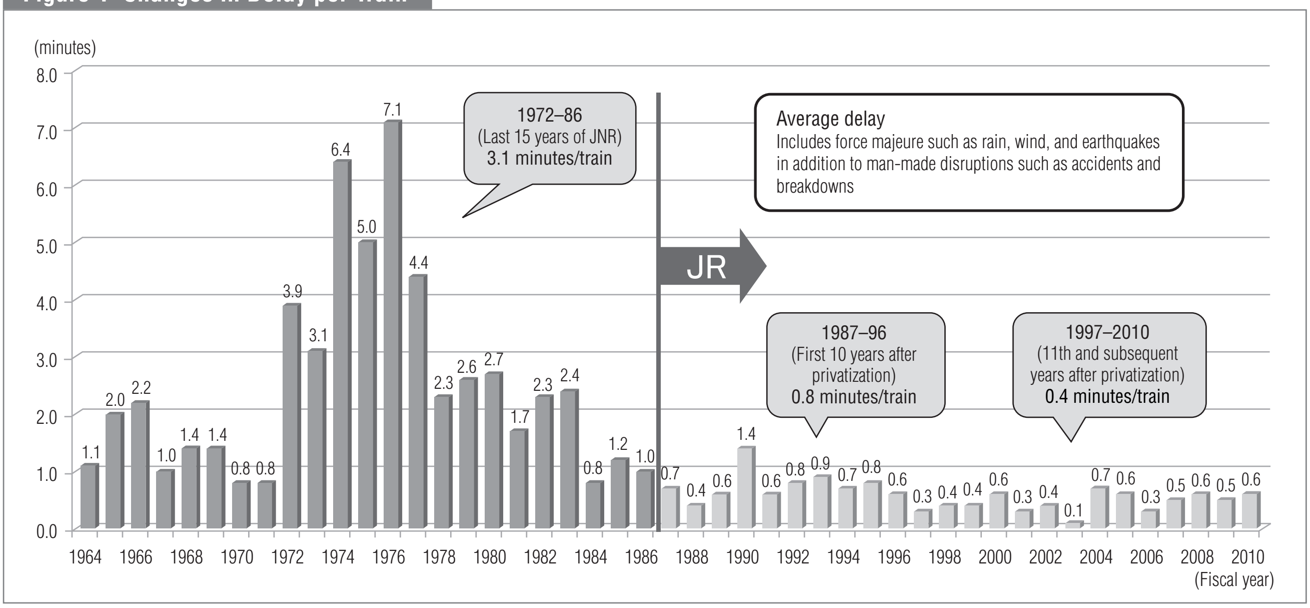
The tsunami after the Great East Japan Earthquake on 11 March 2011 caused huge damage to conventional railway lines along the Pacific coast of Japan's Tohoku region. Since an earthquake in the Tokai region or a triple earthquake in the Tokai, Tonankai, and Nankai area could cause a tsunami of the same size, the disaster preparedness of railways in these regions must be studied. This article reviews earthquake countermeasures for the Tokaido Shinkansen.

Continuing Evolution

Since JR Central was established in 1987, much work has been done on increasing speeds through introducing new rolling stock; conserving energy; improving ride comfort; enhancing transport capacity by opening new shinkansen station in Shinagawa; improving convenience; introducing new ATC; and securing safe and stable transport by aseismic reinforcement of structures. Services on the Tokaido Shinkansen have been greatly improved, cutting the fastest trip between Tokyo and Shin-Osaka to 2 hours 25 minutes. Some 400 daily operations on the Tokaido Shinkansen arrive with an average delay per train of 0.4 minutes and there has never been an accident resulting in a passenger fatality (Figure 1).

These improvements have been achieved by pro-active measures with the top priority on securing safe and stable transport. In countermeasures against natural disasters, for example, works such as slope protection has helped achieve resistance to heavy rainfall. In earthquake countermeasures, civil-engineering structures have been reinforced using aseismic design. To stop trains quickly in an earthquake, the Tokaido shinkansen EaRthquake Rapid Alarm System (TERRA-S) and other systems have been introduced. Total investment since 1987 and including FY2012 to support safe and stable transport has reached ¥2.7 trillion with approximately ¥150 billion invested annually in recent years (Figure 2).

Figure 1 Changes in Delay per Train



Technology Developments at Komaki Research Centre

Railway operations depend on people with different skills working diligently together. Securing safety and enhancing future business depends on improving technical abilities. To achieve this goal as well as train and educate employees, JR Central established its own R&D facility in Komaki City, Aichi Prefecture, in July 2002. The Komaki Research Centre covers a wide area and incorporates large test machines (Figure 3) as well as full-scale viaducts, embankments, and other civil-engineering railway structures. These have been used to develop the series N700A shinkansen rolling stock, to improve maintenance and management of structures, and to develop countermeasures to natural disasters, such as earthquakes and heavy rainfalls.

The N700A development included studies using the Vehicle Dynamic Simulator on introducing a body inclining system to improve ride comfort when running through curves at 270 km/h. (Figure 3, left). A Rolling Stock Field Test Simulator (Figure 3, right) was also introduced in April 2008 to re-create running of shinkansen rolling stock while stationary. It works by operating rolling stock on track wheels to simulate rails and reproduces running conditions by simulating various vibrations. Efforts are underway to optimize safety, stability and ride comfort, while cutting weight and conserving energy.

In addition to test experiments, unique simulation technologies are being developed, including dynamic simulation that models running trains, tracks, and structures and for simulation of damage to reinforced concrete.

Another characteristic of the Komaki Research Centre is that it is in an environment where general issues that encompass the fields of transport, rolling stock, ground facilities and track, and electricity can be actively worked on. A major result has been development of derailment and deviation prevention measures drawing lessons from the Joetsu Shinkansen derailment during the Mid Niigata Prefecture Earthquake in October 2004. As a new countermeasure against earthquakes for the Tokaido Shinkansen, devices are being studied that prevent as much as possible train derailment and deviation from tracks in an earthquake and secure running safety for trains. Based on those results, countermeasure constructions for railway facilities such as track, embankments, and viaducts and for rolling stock are being realized, and various countermeasures are currently being taken.

Earthquake Countermeasures for Tokaido Shinkansen

Overview

One of the most important measures for supporting safe and stable transport by the Tokaido Shinkansen

Figure 2 Capital Investment in Safety

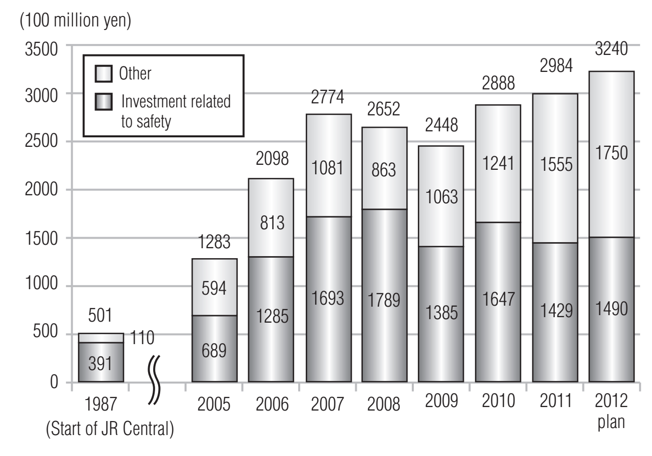


Figure 3 Vehicle Dynamic Simulator (left) and Rolling Stock Field Test Simulator (right)

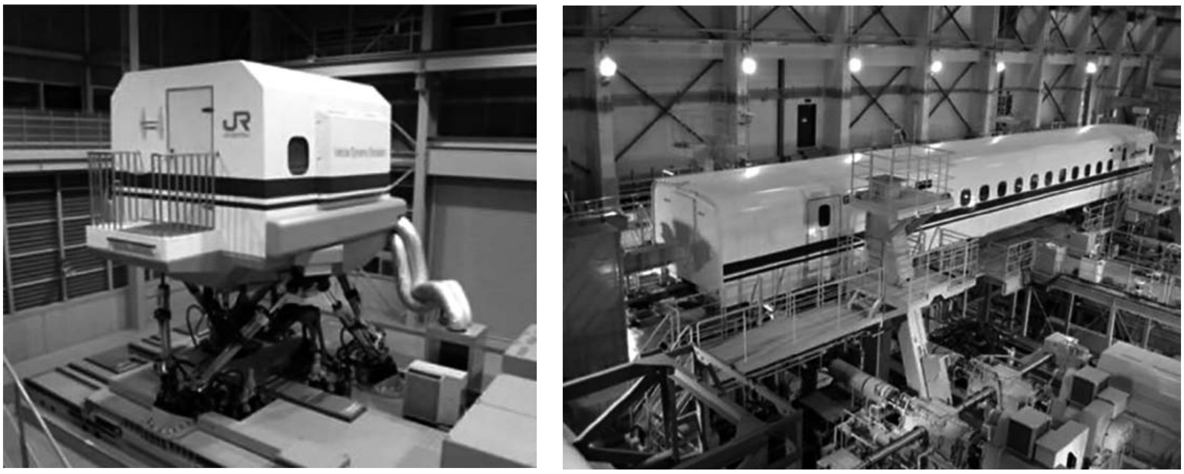
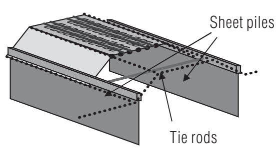
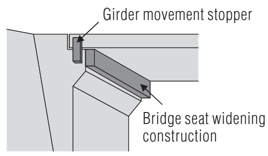
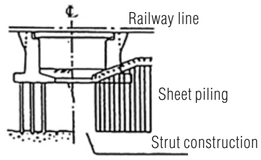


Table 1 Earthquake Countermeasures in Areas Subject to Intensified Measures against Earthquake Disasters (1976 – 96)

<table>
<tr><th>Embankment reinforcement</th><th>Bridge collapse prevention construction</th><th>Reinforcement behind bridge abutments</th></tr>
<tr>
<td>

[Sheet piling cofferdam construction]</td>
<td>

[Bridge seat widening construction/ Girder movement stopper]</td>
<td>

[Strut construction]</td>
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<tr><th>Bridge pier reinforcement</th><th>Slope reinforcement</th><th>Tunnel reinforcement</th></tr>
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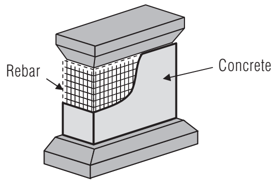
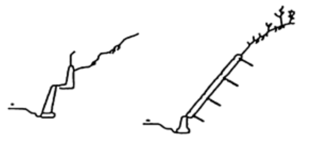
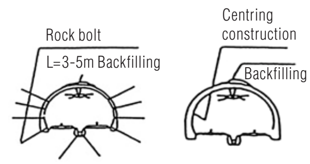
<td>

[Reinforced-concrete jacketing]</td>
<td>
[Retaining wall] [Slope face protective construction]</td>
<td>

[Rock bolt anchor construction] [Backfilling]</td>
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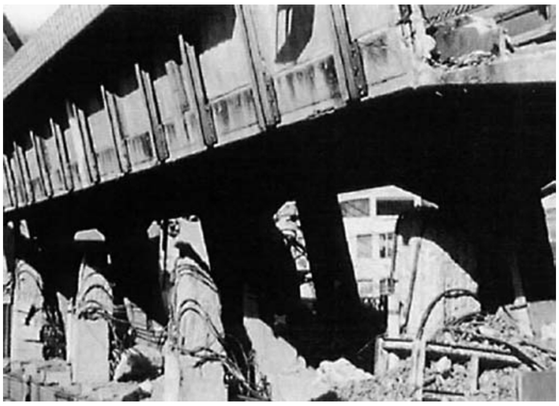
Figure 4 Damage to Reinforced-Concrete Viaducts in Great Hanshin Earthquake


Shear failure


Flexural failure

Figure 5 Standard Reinforcing Method for Viaducts

Reinforcing by Steel Jacketing

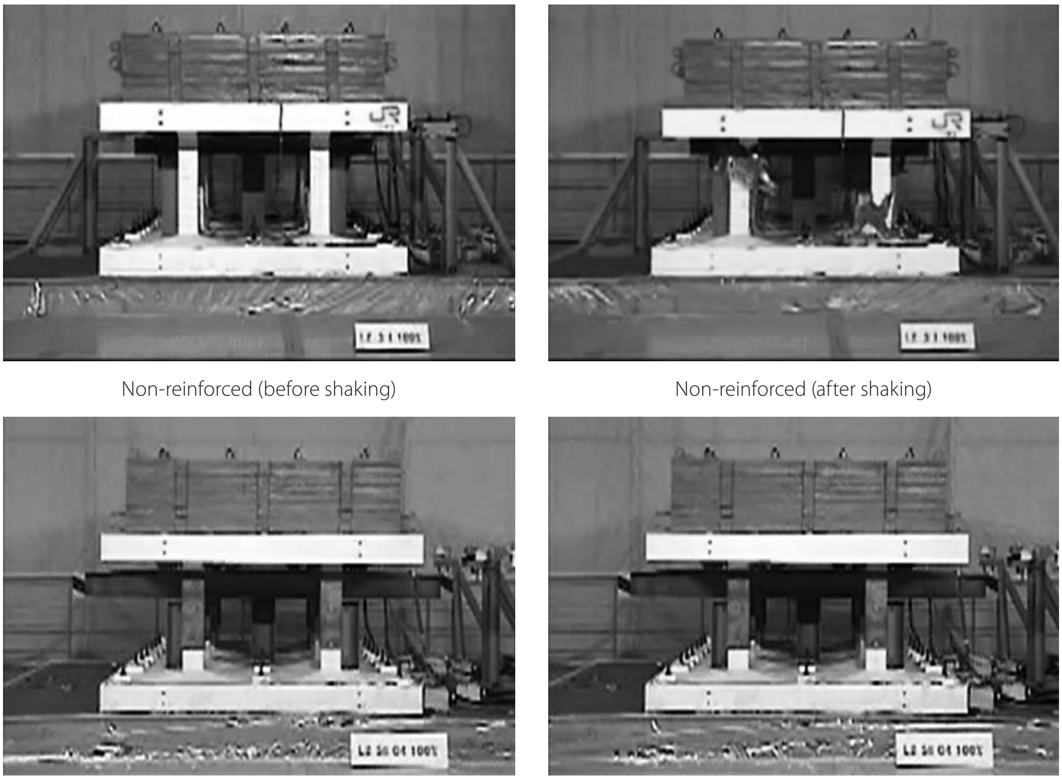
is countermeasures against earthquakes. Earthquake countermeasures for civil-engineering structures on the Tokaido Shinkansen have been implemented steadily from 1979 in the Japanese National Railways (JNR) era. Most of those have been completed for areas where long-term blockage could occur as a result of the Level-2 (extremely rare earthquake motion defined in Japanese seismic design codes) seismic motion of the Great Hanshin Earthquake and the seismic motion of the theoretical Tokai Earthquake that was simulated in 2003.

After the Joetsu Shinkansen derailment during the 2004 Mid Niigata Prefecture Earthquake, JR Central studied new earthquake countermeasures mainly at the Komaki Research Centre to prevent derailment and spread of damage caused by deviation.

The result was new installation of dual-redundunt derailment and deviation prevention methods, consisting of

Figure 6 Shaking table testing of 1/5-Scale Model Reinforced-Concrete Viaducts

Level-2 (extremely rare earthquake motion defined in Japanese seismic design codes) Seismic Motion



Non-reinforced (before shaking)

Non-reinforced (after shaking)

Reinforced by steel jacketing (before shaking)

Reinforced by steel jacketing (after shaking)

derailment prevention guard deviation-prevention stoppers, and countermeasures to control large displacement of structures and tracks.

Earthquake countermeasures from the early days of the Tokaido Shinkansen can be separated into the following two categories: aseismic reinforcement of civil-engineering structures, and measures to stop trains quickly before the main strike.

Aseismic reinforcement of civil-engineering structures

Measures before Great Hanshin Earthquake

Following the 1978 Miyagiken-oki Earthquake, the Act on Special Measures Concerning Countermeasures for Large-Scale Earthquakes specified ‘areas subject to intensified earthquake countermeasures’ for 214 km between Shin-Yokohama and Toyohashi on the Tokaido Shinkansen. Aseismic reinforcement (Table 1) was conducted on embankments (17.9 km), behind bridge abutments (159), on retaining walls (3.6 km), on slope faces (22 locations), for bridge collapse prevention (3033 locations), on viaducts (144 locations), on bridge piers and abutments (55), and in tunnels (18.2 km).

Measures after Great Hanshin Earthquake

- Aseismic reinforcement of reinforced-concrete viaducts

  During the Great Hanshin Earthquake, reinforced-concrete columns of the San’yo Shinkansen viaduct suffered severe shear and flexural failure, resulting in viaduct collapse (Figure 4). Recovery restoration from the flexural failure took much less time than the 3 months required to recover from the damage caused by shear failure.

The Tokaido Shinkansen was further from the epicentre and only suffered relatively minor damage. Countermeasures taken in light of this earthquake involved jacketing its shear-critical concrete columns in steel (Figure 5). All 17,600 susceptible columns had been remediated by 2008. The effectiveness of steel jacketing was validated by numerical analysis along with load testing on models of standard reinforced-concrete viaducts. Shaking tests of 1/5-scale models of reinforced-concrete viaducts proved the resistance to Level-2 seismic motion (Figure 6).

Meanwhile in May 2003, the Cabinet Office announced the predicted seismic acceleration of the theoretical Tokai Earthquake. Since movement in excess of Level 2 is predicted for areas struck by the theoretical Tokai Earthquake, the aseismic performance of flexure-critical columns was also raised and another 2000 flexure-critical columns on the Tokaido Shinkansen were reinforced from 2005 as an extra measure.

At locations under viaducts where reinforcing using steel jacketing was difficult, such as stations, pre-assembled steel plates and damping braces were used after confirming performance equivalent to the standard jacketing method (Figure 7). In total, some 19,600 reinforced-concrete viaduct columns were reinforced.

- Aseismic reinforcement of reinforced-concrete bridge piers

About 1100 shear-critical, reinforced-concrete bridge piers were reinforced after 1995 in addition to the 55 piers where countermeasures had already been made since 1979. Further countermeasures are now underway (planned completion in 2014) on some 200 flexure-critical bridge piers that are predicted to fail if hit by the theoretical Tokai Earthquake. The aseismic reinforcement uses reinforced-concrete and steel plates.

- Aseismic reinforcement of embankments

Embankments failed extensively in the Niigata (1964), Tokachi-oki (1968 and 2003), and Mid Niigata Prefecture earthquakes (2004) (Figures 8 and 9). The failures were classified by experiments on model embankments, and other tests to propose reinforcement methods. Based on the new type A and B failure proposals, major damage was predicted, requiring long periods before service restoration, so countermeasures were taken from 1979 on sections covering about 17.9 km (Table 2). Moreover, additional countermeasures were completed on about 6.5 km of the Tokaido Shinkansen from 2005 to 2009 to prevent major damage requiring long service-restoration times. With that, countermeasures against the above two failure proposals were completed. In areas where the theoretical Tokai Earthquake would cause major damage, destruction to type-C and D embankments in Level-2 seismic motion is expected. Within that area, we selected a further 2.9 km where Level-4 deformation is predicted. The area has been the target of additional countermeasures since 2008 (planned completion in 2013). The effectiveness of sheet piling cofferdam construction has been modelled; sheet piling cofferdam is the standard aseismic reinforcement method for type-A and B failures. An overview of the construction is shown in Figures 10 and 11 along with photographs of completed construction.Sheet piling up to 3 m in the liquefied layer directly below the embankment has proved effective for embankments on ground experiencing liquefaction in type-B failures.

Figure 7 Special Reinforcement Methods for Reinforced-Concrete Viaducts

Assembly of steel plates — Damping braces

Figure 8 Circular Slip Including Support Ground

Mid Niigata Prefecture Earthquake

Figure 9 Levee Body Longitudinal Cracking Due to Liquefaction of Support Ground

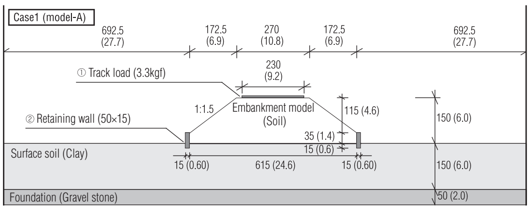
Left: 2003 Tokachi-oki Earthquake, centre and right: 1968 Tokachi-oki Earthquake

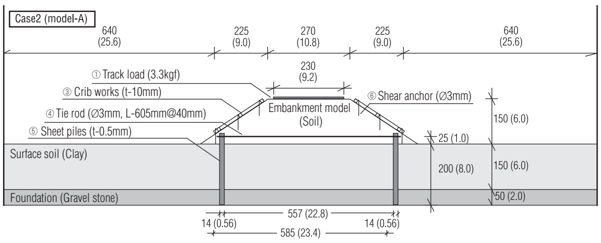
Table 2 Embankment Failure Forms and Reinforcement Methods

Classification	Purpose of countermeasures	Prevention of long-term blockage		Running safety
	Failure form	Theoretical Tokai Earthquake measures	Additional (Level 2 earthquake) measures for all lines	Measures to prevent derailment/deviation
A	Weak cohesive ground Sinking due to circular slip including ground	Tie rod ④ Sheet piles Sheet piles (support layer) + tie rods • N ≤ 4	Tie rod ④ Sheet piles Sheet piles (support layer) + tie rods • N ≤ 4	N/A
B	Liquefied ground Subsidence due to ground liquefaction	Tie rod ④ Sheet piles Sheet piles (support layer) + tie rods • Liquefied ground	Tie rod ④ Sheet piles GL-3m Sheet piles (GL –3 m) + tie rods • Liquefied ground	N/A
C	Slightly weak sandy soil ground Subsidence due to circular slip of embankment	Soil covering/nailing ④ Soil covering/nailing method • N ≤ 15 and 6 m ≤ H • 9 m ≤ H (normal ground)	N/A	Soil covering/nailing ③ Soil covering/nailing method • Level 2 earthquake N ≤ 15 and 6 m ≤ H • Theoretical Tokai Earthquake 15 < N ≤ 20 and 6 m ≤ H
D	Slightly weak cohesive soil ground Subsidence due to shaking around boundary between embankment and ground	④ Sheet piles (GL –1 m) + tie rods Or tie rods utilizing retaining walls • 4 < N ≤ 5 and 3 m ≤ H	N/A	Soil covering/nailing ③ Soil covering/nailing method • Level 2 earthquake 4 < N ≤ 6 and 3 m ≤ H • Theoretical Tokai Earthquake 5 < N ≤ 6 and 3 m ≤ H
E	Normal ground Gentle embankment subsidence	N/A	N/A	② Construction to prevent ballast flow out • All embankment sections including applicable locations

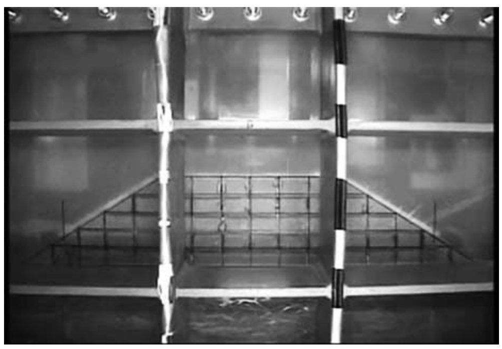
(Circled numbers are deformation level when not reinforced)

Figure 10 Confirmation of Reinforcement Effects by Model Experiments





Non-reinforced (after vibration)



Reinforced by sheet piling (after vibration)

Figure 11 Aseismic Reinforcement Method for Embankments

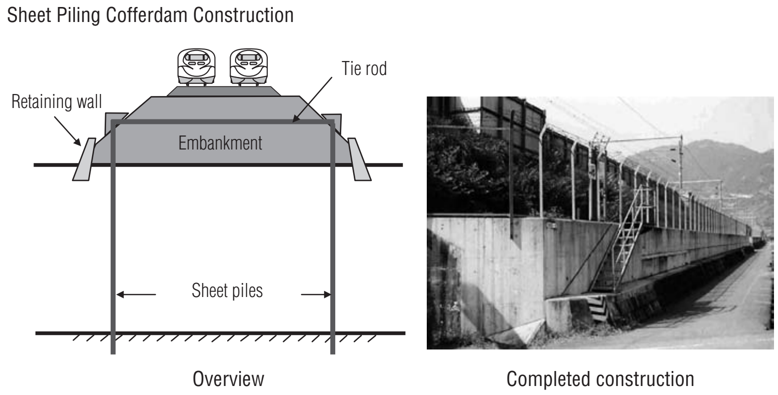
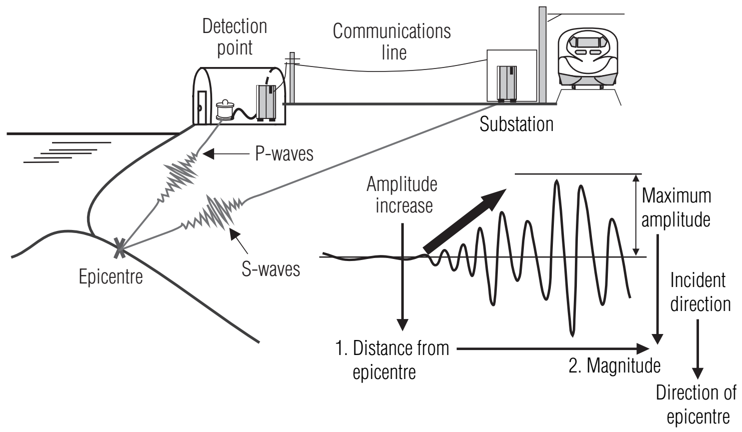


Figure 12 Tokaido Shinkansen Earthquake Rapid Alarm System (TERRA-S)



Measures to stop trains quickly

Measures to stop trains quickly in an earthquake are composed of coastal seismometers (from 1965), TERRA-S (from 1992), and earthquake early warnings from the Meteorological Agency (from 2008).

The TERRA-S system uses remote seismometers to detect the first small primary waves (P-waves) and calculate the earthquake size and epicentre in about 2 seconds (Figure 12). Both the TERRA-S (at 21 locations) and coastal seismometers (50 locations) issue immediate warnings when the safe threshold is exceeded, and cut power from substations to bring running shinkansen to an emergency stop—hopefully before the main wave strikes—and increasing safety. Following the 2011 Great East Japan Earthquake, P-wave detection warnings on coastal seismometers have been augmented and functionality in terms of multi-plate earthquakes has been strengthened, increasing safety. In measures for rolling stock, train emergency braking performance has been increased. Work is also underway to reduce the series N700 braking distance.

Figure 13 Earthquake Countermeasures for Tokaido Shinkansen

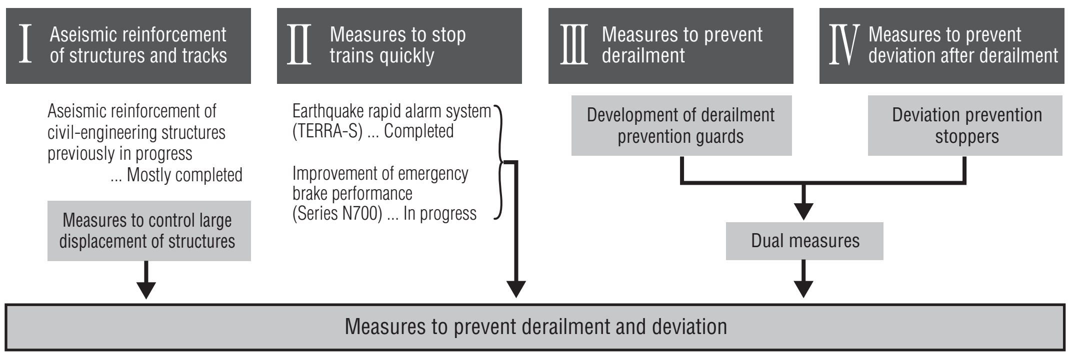


Table 3 Measures to Prevent Derailment and Deviation for Tokaido Shinkansen

For	Track and Rolling stock	Track	Embankments	Viaducts
Specific items considered	• Preventing derailment as far as possible • Preventing deviation after derailment as far as possible	• Track deformation/ buckling due to ballast flow out	• Track deformation/buckling due to subsidence of embankments • Vertical displacement behind bridge abutments	• Unevenness between viaducts • Amplification of viaduct swaying
Details of countermeasures	• Derailment prevention guards • Deviation prevention stoppers	• Ballast flow out countermeasures	• Countermeasures against subsidence of embankments • Measures behind bridge abutments	• Countermeasures to unevenness • Countermeasures to displacement

Measures to prevent Tokaido Shinkansen derailment and deviation

Following the Joetsu Shinkansen derailment during the Mid Niigata Prefecture Earthquake, JR Central examined new derailment countermeasures from four perspectives (Figure 13 and Table 3), based on items such as the Joetsu Shinkansen derailment conditions and Tokaido Shinkansen track structure and layout. The perspectives are derailment prevention guards, ballast flow out, embankment subsidence, and viaduct unevenness and displacement (Table 3).

- Derailment prevention guards

  These guards are positioned parallel and close to the track rails to prevent derailment as shown in Figure 15. There are various designs but the convertible type was used for ease of maintenance (Figure 14). Tests confirmed their effectiveness against rocking derailment like that in the Mid Niigata Prefecture Earthquake and maintenance problems on main-line tracks.

  The effectiveness for rocking derailment was confirmed for various seismic waves using full-scale tests on actual bogies (Figure 16). Among the shakes in the tests, 1.0 time waveform in the displacement of the theoretical Tokai Earthquake was used. The maximum lateral acceleration and displacement of the waveform is 1,300 gal and 333mm, respectively. Vibration tests on a 1/5-scale model confirmed the effectiveness against various waves, which cannot be recreated using full-scale tests due to device constraints. Derailment prevention guards are effective up to 1.4 times the displacement amplitude waveform in the theoretical Tokai Earthquake. Moreover, to confirm the effect that running speed has on the derailment mechanism, we performed 1/10-scale model vibration tests on roller rig. As the adhesion between the wheels and rails decreased as speed increased, we confirmed that there is no difference in the derailment mechanism during an earthquake between a vehicle running at high speed and a stationary one, although the derailment itself occurs more easily when a vehicle is running. Moreover, we built a simulation model using data from full scale tests on actual bogies and confirmed that the main cause of rocking derailment in an earthquake is a lateral motion but not a vertical one.

  Installation tests on main-line track (Figure 17) showed no problems with installing derailment prevention guards nor

Figure 14 Overview of Derailment Prevention Guards

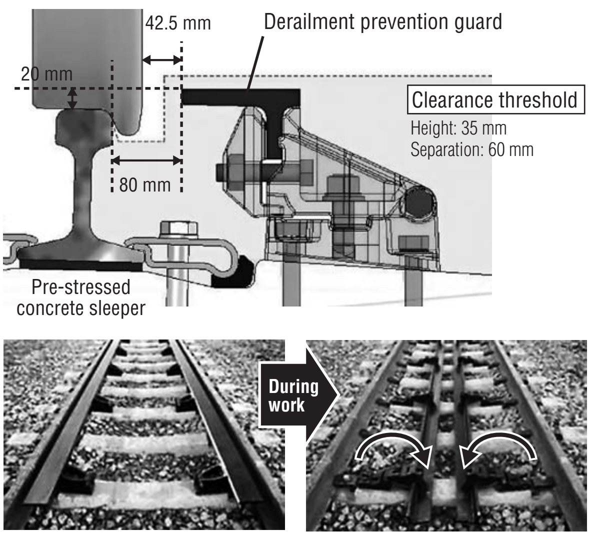


Figure 16 Full-Scale Test on Actual Bogie

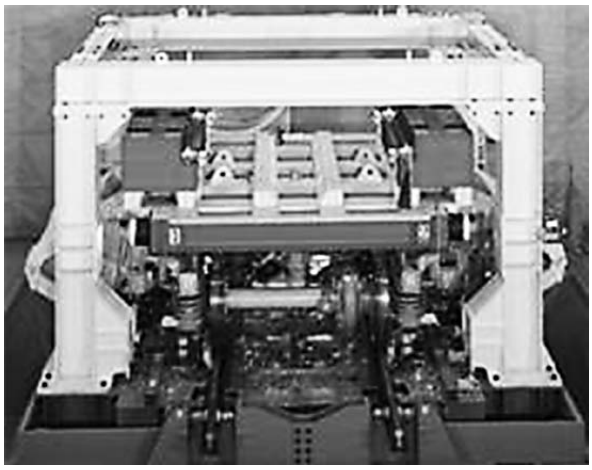


Figure 15 Effectiveness of Derailment Prevention Guards to Rocking Derailment

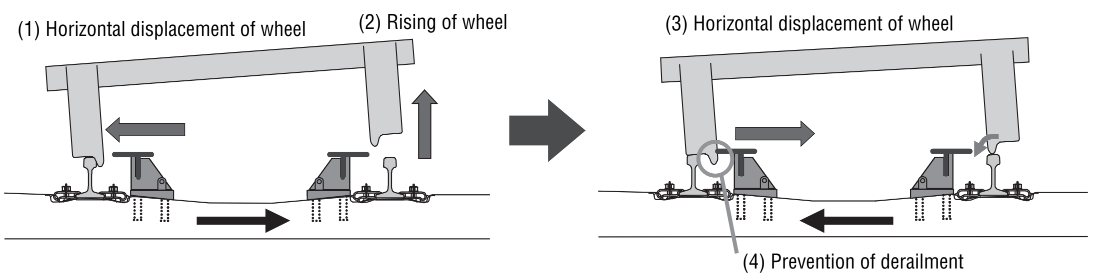


Figure 17 Derailment Prevention Guards on Main-Line Track

Figure 18 Countermeasures to Ballast Flow Out

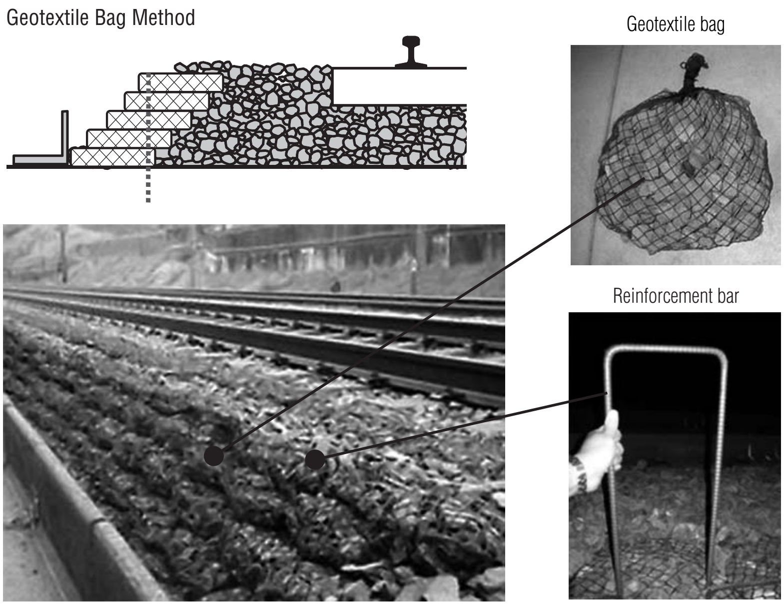


Figure 19 Countermeasures to Ballast Flow Out (Theoretical Tokai Earthquake)

Non-reinforced (before shaking)

Non-reinforced (after shaking)

Geotextile bag method (before shaking)

Geotextile bag method (after shaking)

with running of trains after installation. Checks more than 1 year after installation showed no change in position due to running of trains, etc. Moreover, there were no functional problems in terms of track circuits and signals. Effectiveness, ease of installation, and maintenance all proved satisfactory.

- Ballast flow out

The Tokaido Shinkansen uses ballasted track. Ballast moves during an earthquake, deforming the track configuration and causing buckling. Earlier countermeasures to ballast flow out use concrete curbs weighing 150 to 200 kg each, positioned on the outside of tracks like a retaining wall.

For derailment prevention guards to function, sleepers on ballasted track must not suffer lateral displacement of more than 30 mm. That target value is set based on the maximum displacement of sleepers in the range at which derailment prevention guards were confirmed to function in vibration tests using actual bogies for a theoretical earthquake (Level-2 seismic motion and seismic motion of the theoretical Tokai Earthquake). Moreover, this countermeasure keeps lateral displacement of sleepers to 30 mm and maintains track form.However, heavy curbs are hard to handle with accuracy and the track must be closed during construction. To solve these problems we developed a new, efficient method using 25-kg geotextile bags piled on the slope and secured with driven reinforcement bars (Figure 18). Full-scale shaking tests proved this method has the same earthquake resistance as conventional concrete curbs (Figure 18).

- Embankment subsidence

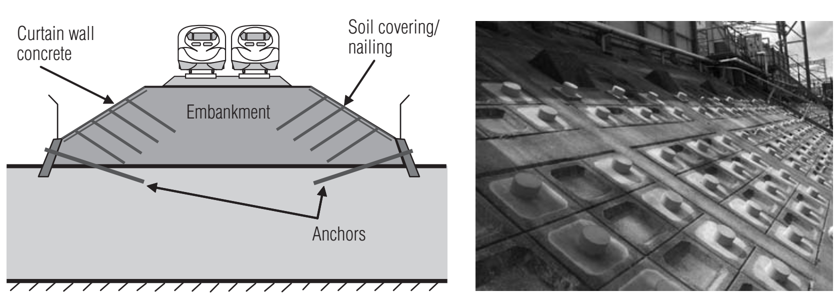
If embankment subsidence in an earthquake can be kept to less than 20 cm, deformation of more than 20 cm, which is equivalent to the height of sleepers, will not occur when combined with ballast flow out countermeasures because the track configuration is maintained. We chose soil covering/nailing to constrain embankment deformation due to slope shoulder subsidence at locations subject to Level-2 seismic motion, and Level-3 deformation (20 to 49 cm subsidence) in the theoretical Tokai Earthquake, or type-C or D failures (Table 2). An overview of the soil covering/nailing method is shown in Figure 20.

- Viaduct unevenness and displacement

Response analysis of standard Tokaido Shinkansen viaducts in the theoretical Tokai Earthquake shows the viaduct crown will sway 30 cm + 26 cm (amplification) in response to ground surface movement of 30 cm if no earthquake countermeasures are taken. However, when countermeasures using X-shaped damper braces (Figure 21) are taken, the swaying is 30 cm + 3 cm (amplification), reducing the amplification displacement by 88.5%. Misalignment must be controlled because localized irregular misalignment occurs easily due to unevenness between adjacent viaducts with over-hanging structures (Figure 22). The target misalignment is set to the acceptable horizontal unevenness in an earthquake (3 cm) based on railway displacement limit design standards.

Horizontal displacement is about 3 cm when using viaduct displacement countermeasures, and horizontal unevenness is assumed to be about 6 cm when adjacent viaducts respond out of phase. We confirmed that displacement could be further reduced to about 2 cm (approximately 30% of the assumption) using unevenness countermeasures, meeting the requirement of about 3 cm.

Figure 20 Countermeasures to Embankment Subsidence (Soil Covering/Nailing)



Overview　　Completed construction

Figure 21 Viaduct Displacement Countermeasures

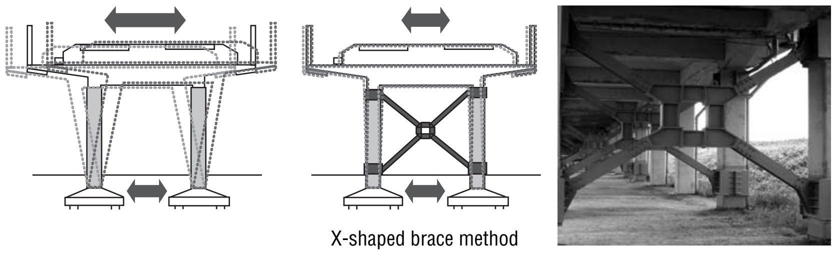
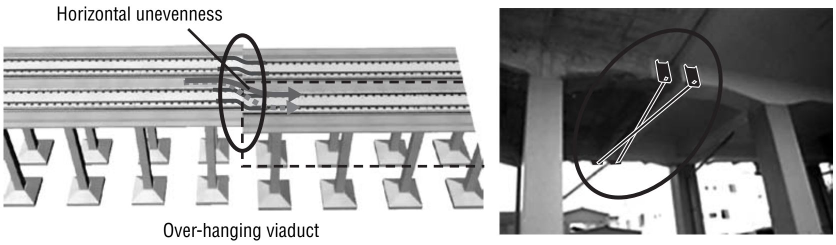
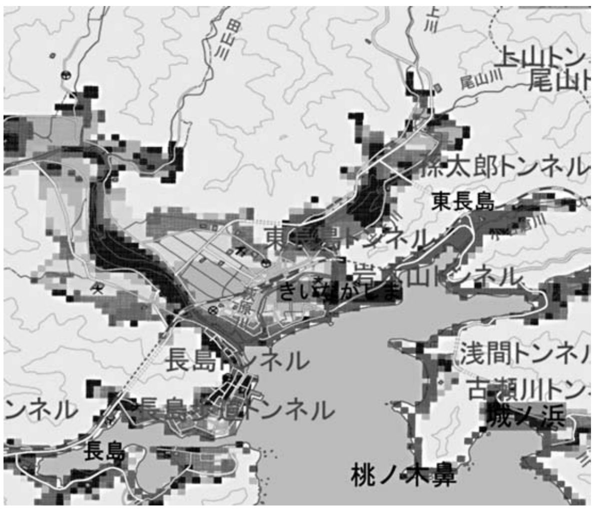


Figure 22 Countermeasures to Viaduct Unevenness



Over-hanging viaduct　　Steel bars for pre-stressed concrete

Figure 23 Local Government Hazard Map (Mie Prefecture)



Tsunami countermeasures

The catastrophic damage caused by the tsunami after the Great East Japan Earthquake reconfirmed the need to evacuate passengers safely and quickly rather than simply strengthening facilities.

Following the devastating 2003 Sumatra Earthquake tsunami, JR Central has been working with university researchers on predicting damage from tsunami. The tsunami height is simulated using a detailed 5-m mesh, and locations at risk are defined taking into consideration information from hazard maps (Figure 23) created by local

Figure 24 Efforts in Tsunami Evacuation

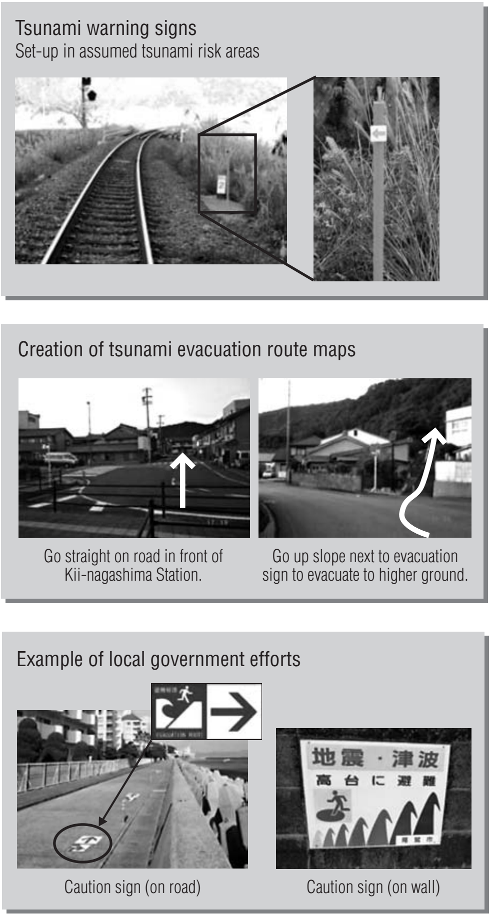
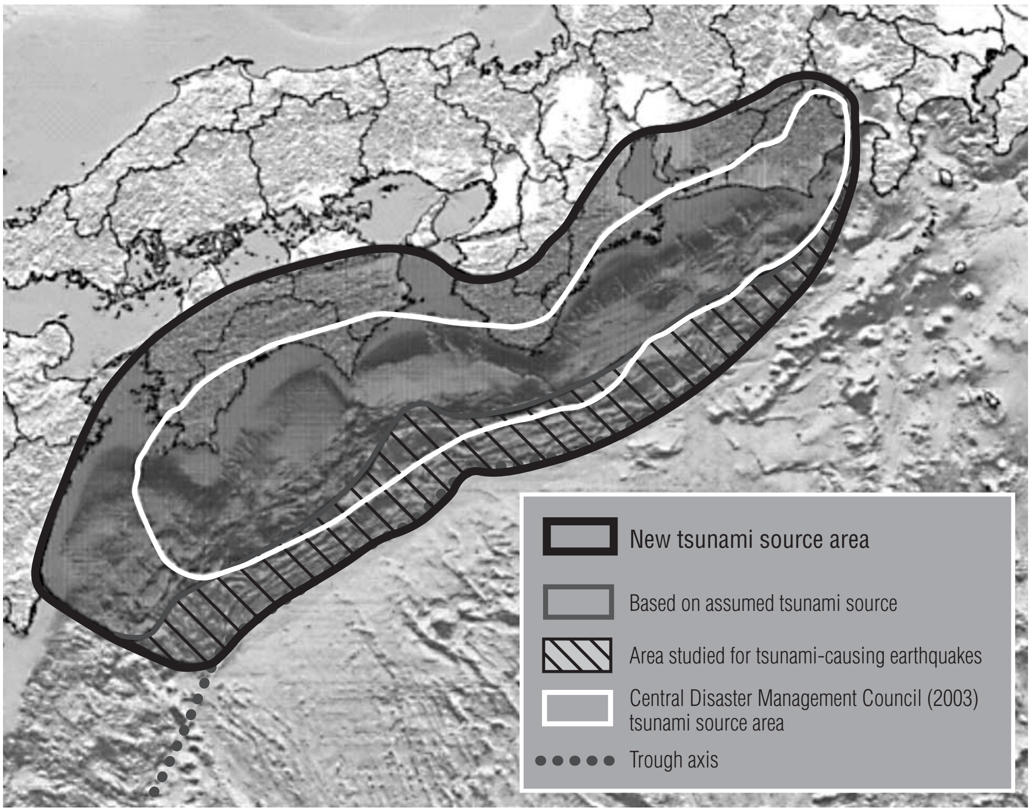


Figure 25 Tsunami Evacuation Drill

1 September 2011: Tsunami evacuation drill held by stopping special train between Kii-nagashima Station and Umegadani Station

Figure 26 Cabinet Office Central Disaster Management Council Revised Tsunami Source Area



governments. Tsunami risk locations are being revised as new hazard maps are released by local governments. In December 2011, Mie Prefecture revised the tsunami risk assuming a triple earthquake strike in the Tokai, Tonankai, and Nankai areas. The 2003 assumptions of the Cabinet Office Central Disaster Management Council for this type of triple earthquake assumed no tsunami risk for the Tokaido Shinkansen, putting only some parts of conventional lines at risk. The December 2011 reassessment of tsunami risk led to revised evacuation guidance and to tsunami evacuation drills (Figures 24 and 25).

After the Great East Japan Earthquake, we simulated tsunami flooding for a Magnitude 9.0 triple earthquake in the Tokai, Tonankai, and Nankai areas (Figure 26). Even with a tsunami of twice the height of the 2003 assumptions, nowhere on the Tokaido Shinkansen would be flooded because the tracks are kilometers from the coast and most civil-engineering structures such as viaducts, bridges and embankments are 6 m or higher above ground level.

Estimates of seismic intensity distribution and tsunami height for a major earthquake in the Nankai Trough (location of Magnitude 9.1 earthquake) were released by the Cabinet Office Central Disaster Management Council study group on 31 March 2012. Hazard maps are being revised by local governments taking into account the supposed flooding and we intend to revise the assumed tsunami risk areas as necessary along with the required actions for conventional lines.

Conclusion

Disaster preparedness has been enhanced for civil-engineering structures but further countermeasures taking into account aging and fatigue will probably be needed in the future.

Specific issues are weld fatigue on steel bridges, neutralization of aged reinforced-concrete structures, and effects of vibration and air pressure in tunnels. Since the establishment of the Technology Research and Development Department, we have been focussing on maintenance and enhancement of civil-engineering structures as a key issue. We have learned much in the past 10 years through work on on-site situation analysis, full-scale model testing, and analysis. A major issue for the future is how to perform reasonable maintenance and enhancement at the best time.

We are also working to create a second route along Japan's key transport artery by constructing the Chuo Shinkansen maglev. This will help assure continuity of communications and transport in a disaster as well as help support and maintain Japan's economy. ■

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