Technological Development to Improve Cross-cutting Seamlessness Earthquake Countermeasures

Yoshitaka MURONO
Center for Railway Earthquake Engineering Research

It is important to reinforce the “robustness” and “restoration capacity” of railways for them to be more resilient not only against expected earthquakes but also against anticipated earthquakes. It is therefore important to respond to the earthquake in four steps in terms of timing: response before the earthquake, emergency response at the time of the earthquake, initial response immediately after the earthquake and restoration/recovery response after the earthquake. Since railway systems comprise numerous facilities, a range of seismic countermeasures have to be designed covering all components: civil engineering structures, catenary masts, and vehicles etc. Responses both at each stage of the emergency and in relation to each of these components during a seismic emergency should dovetail seamlessly. This report therefore introduces the latest technology that enables the establishment of seamless earthquake countermeasures.

Keywords: seamless anti-quake measures, robustness and restoration capacity

1. Introduction

Railway systems must be “robust” and possess “recovery capacity” to be resilient to earthquakes (Fig. 1). In order to enhance robustness against earthquakes, “pre-earthquake improvements” is critical, which means designing and constructing earthquake-proof structures or carrying out seismic retrofitting on existing structures. Post-quake restoration capacity can be enhanced through “pre-earthquake improvements” and “post-quake response” (covering “emergency response” and “initial response”). The vital purpose of “pre-earthquake improvement” is to ensure that a catastrophe situation is averted, which means putting measures in place that factor in the possibility that an earthquake will be stronger than anticipated. The primary aim of “emergency response” measures is to raise the alarm before a strong seismic ground motion arrives in order to ensure the evacuation and safety of users and employees. “Initial response” measures include planning patrol inspections, recovery, and staffing/materials procurement based on extensive information collected immediately after the earthquake. “Recovery response” measures refer to actions actually taken to restore services.

This paper discusses some of the recent undertakings by RTRI aimed at enhancing the “robustness” and “recovery capacity” of railways.

2. Actions to enhance “robustness” against earthquakes

(1) Enhancing “robustness” against shaking

New structures should be designed in strict accordance with Design Standards for Railway Structures while anti-quake measures should be applied to existing structures. The Design Standards for Railway Structures (hereafter the “Seismic Standards”) were revised in 2012 [1], and structures constructed as per the revised standards meet extremely high levels of safety.

In the case of existing structures, following the 1995 Hyogo-ken Nanbu Earthquake, railway operators actively began seismically reinforcing structures in compliance with a notification issued by the Ministry of Land, Infrastructure, Transport and Tourism. For example, existing reinforced concrete structures have been further strengthened mostly through steel plate lining methods to prevent shear failure. River bridges however, which are difficult to reinforce using this lining method have been retrofitted over the past few years with vibration control dampers. As such, a practical design method was developed for bridges with friction dampers, a type of damper which is easy to apply [2]. Efforts are also being made to develop negative stiffness dampers, which are more effective in controlling vibration [3].

(2) Enhancing “robustness” against surface fault displacement

The ‘Seismic Standards’ were drafted on the premise that main effects of an earthquake would be “shaking.” In the case of a major earthquake however, bedrock containing a fault may rise through the sedimentary layer and break through the ground surface (surface fault displacement). To wit, there have been reports of structures that...
have suffered direct damage due to such displacement. The Seismic Standards classify surface fault displacement as “a phenomenon accompanying an earthquake” and, given the current level of technology, do not offer a specific design method to counter such an event [1]. Consequently, RTRI started working on surface fault displacement.

Research on the size of surface fault displacements recorded from past inland active fault earthquakes found that displacements in quakes with a moment magnitude \((Mw)\) of around 7.0 averaged around 1 m while some cases arising in quakes of around \(Mw 7.5\) exceeded 3 m. In addition, a method was developed for calculating theoretical surface fault displacement in homogeneous soil. Figure 2 shows calculated displacements for the case of an earthquake of \(Mw 7.0\) during which a reverse fault occurs with uniform slippage along the fault plane. The displacement directly above the fault measured around 1 m, corresponding to the results of previous research. It was also found that, for earthquakes of the same magnitude, the shallower the fault, the greater the maximum displacement but the smaller the range of the impact.

The impact of surface fault displacement on bridges and viaducts was also studied. With horizontal faults, it was found through numerical analyses and experiments that the angle at which a fault and a bridge/viaduct cross each other has a significant influence. When the crossing angle is less than 90°, the collapse of and damage to bearings mostly affect the span that straddles the fault alone, whereas when the crossing angle is more than 90°, wider damage occurs [4]. With vertical faults, the following was found: (i) footing beams are essential in that, without them, even a small fault displacement can cause significant damage to upper beams; and (ii) overhang-type viaducts are effective in eliminating the risk of collapse [5].

(3) Enhancing “robustness” against liquefaction

An anti-liquefaction method was developed whereby the risk of liquefaction can be minimized by injecting a relatively small volume of chemicals into the soil in dendrite patterns (Fig. 3). In this method, the time taken for the solution to solidify, the solution’s viscosity and other parameters are adjusted appropriately before a solution of chemicals is injected into the ground in dendrite patterns. The dendrite structures then compact the surrounding soil and enhance its resistance to liquefaction. The dendrite structures be arranged in various directions to extend across the entire mass of ground that needs to be improved.

Results from field tests with a 10% injection (around 1/3 of the injection volume of the conventional method) in dendrite patterns, showed that the Nd value which indicates ground hardness, ground density, and the coefficient of earth pressure at rest which indicates lateral pressure, all improved. Based on these test results, calculations were made on the possibility of the ground becoming liquefied as well as the extent of damage caused by liquefaction. It was found that administering the injection reduced liquefaction to such an extent that its impact on structures could be ignored.

The method enables ground improvement with lower injection volumes, and thus costs less and can be completed faster than the conventional method. The method also is associated with smaller upheaval and irregular displacement of the ground surface and therefore can be administered directly below existing railway structures. Furthermore, injection machines are small enough to be deployed in restricted spaces. All these benefits should expand the method’s applications.

3. Actions to enhance “restoration capacity” after earthquakes

(1) Enhancing “pre-earthquake recovery capacity”

Enhancing recovery capacity in the design process prior to an unexpected earthquake is called “anti-catastrophe.” This concept was first introduced in the Seismic Standards for railway structures [1]. The purpose of this kind of measure is to avert a catastrophic situation even when an unexpectedly strong earthquake occurs. Conventional seismic design means that structures must meet required performance criteria set according to a level of earthquake motion referred to in design, whereas anti-catastrophe measures mean the capacity to deal with strong earthquake motion that exceeds these expectations. Two methods were developed to support catastrophe avoiding measures.

A “deadweight compensation structure” was developed to prevent complete collapse in the case of an unexpectedly large earthquake (Fig. 4). Under this structure the deadweight compensation columns can bear the deadweight of the slabs in place of main columns even if main columns collapsed in unexpectedly severe earthquake. Static load-
Deadweight compensation columns: Columns capable of supporting their own weight should main columns (seismically-designed columns) fail

Designed not to transmit horizontal force

Fig. 4  Rigid-frame viaduct with deadweight compensation structure

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Fig. 5  Relationship between load and displacement for deadweight compensation structure

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During tests were conducted using a model rigid-frame viaduct with deadweight supporting columns in order to test the effectiveness of the structure. The tests demonstrated that the deadweight supporting columns had a vertical bearing capability after the main columns were damaged showing that the proposed structure was capable of preventing the total collapse of the viaduct even following significant deformation with a ductility factor of over 50: far beyond the viaduct’s maximum limit (Fig. 5).

In addition, a “collapse direction control structure” was developed to prevent a structure causing more harm by collapsing towards residential areas, emergency transport roads, spaces for restoration operations, etc. in the case of unexpectedly severe earthquakes. For this, two types of simple device, either in the form of a block or a chain, were developed (Fig. 6). Destructive tests were conducted to verify the effectiveness of these two measures for controlling the direction of collapse, using a model rigid-frame viaduct on a shaking table. Two configurations were set up for the test on a shaking table together: one designed to make the structure collapse to the left, and the other designed to make it collapse to the right. The table was shaken with increasing sinusoidal excitation in the resonance domain of the structures. The test found that both the block and chain demonstrated asymmetrical behavior while being shaken, making the model viaducts collapse in the designed directions (Fig. 7).

(2) Enhancing “recovery capacity” for when earthquakes occur

In making emergency responses to an earthquake, the Earthquake Early Warning System should be fully utilized. The system offers earliest detection of tremors and issues a warning before structures shake violently so that trains can be promptly slowed down or stopped. The Earthquake Early Warning System currently in place estimates epicentral distance based on the growing curve of initial P-waves of around two seconds \(^{3}\) and calculates the magnitude using the distance attenuation formula based on the epicentral distance and measured displacement amplitude. Based on the estimated magnitude and epicentral distance, the system swiftly determines the possibility of damage to railway facilities and, whenever necessary, issues warnings to stop trains.

As a substitute for the \(B-\Delta\) method, a new algorithm, the \(C-\Delta\) method, was developed [7]. A growing curve of initial P-waves of around 0.5 seconds was approximated using a linear function, and the relational expression of the gradient \(C\) and epicentral distance was obtained empirically based on existing observed seismic records. This shortened the length of data used for estimation from the conventional two seconds to 0.5 seconds, and improved the accuracy of epicentral distance estimation by around 13% over the conventional method. In addition, as the gradient \(C\) can be impacted significantly by heterogeneity of the condition of the ground, the relational expression for gradient \(C\) and the epicentral distance was revised while taking into consideration regional differences in heterogeneity of propagation speed. The study led to a further 40% improvement in the estimation accuracy of epicentral distance [8]. On a related note, a prototypal seismograph with the new algorithm

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Fig. 4  Rigid-frame viaduct with deadweight compensation structure

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Fig. 5  Relationship between load and displacement for deadweight compensation structure

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Fig. 6  Proposed collapsing direction control structure

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Fig. 7  Results of shaking table test on collapse direction control structure
was completed and preparation is currently underway for its installation on commercial lines.

(3) Enhancing “restoration capacity” immediately after earthquakes

The effectiveness of first response measures, such as patrol inspections, restoration and staffing/materials procurement planning relies on gathering as much information about the magnitude of ground motion and the extent of structural damage, as soon as possible. Currently, railway operators determine the necessity for and the scope of patrol inspections based on information such as seismic intensity and SI values measured at locations where seismographs are installed. This type of information, however, only represents a series of “dots” and does not necessarily reflect shaking along operational “railway lines.” Operations can be restored more quickly and more effectively if the gathered information relates to these “lines” instead of “dots.” Given this background, on June 1, 2015, RTRI started a operation for “an earthquake information distribution system for railways.” For details, see Ref. [9]. The current system estimates the spatial distribution of ground motion (peak ground acceleration, seismic intensity and SI value) based only on public information. However, the system is being improved to forecast structural damage as well, based on data about structures owned by railway operators. The performance of this prototype system is currently being verified. Figure 8 shows peak ground acceleration (PGA) and levels (1 to 4) of structural damage that were forecast along a railway line following an earthquake.

4. Simulator used as a common fundamental technology

“An earthquake disaster simulator for railways” was developed and has since been continuously updated as a common fundamental technology for anti-quake policy formation. The simulator is capable of generating earthquakes of any magnitude in any location, and of computing the propagation of resultant seismic waves across the whole of Japan.

This allows surface ground motion and structural behavior over a distance of several hundred kilometers to be predicted. Railways are basically a long linear structure with various kinds of components including civil engineering structures, catenary masts and vehicles, making it difficult to know what sorts of potential risks exist and where they are. The simulator enables identification of weak points and helps prioritize corrective action. In addition to a real-time version and a dynamic analysis version, an inventory method has also been developed more recently (Fig. 9) [10].

An inventory database (IDB) was constructed, containing structural models stored according to eight parameters. The structural models stored in the IDB are either based on actual designs or artificially created ones. Currently, about three million types of model have been stored. By using the IDB, structural models closely resembling the structures along the line to be analyzed can be selected for dynamic analysis. The method substantially streamlines the modeling operation of structures (in terms of time and cost of analysis) and, even when there is not sufficient information for modeling, can be used to easily evaluate an entire line even though irrelevance rate of selected models may be higher.

5. Conclusion

As part of the foundation of socio-economic activity, railways are expected to be resilient to large anticipated earthquakes. RTRI is continuing to make contributions to this end through research, development and information dissemination.

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Author

Yoshitaka Murono, Dr. Eng.
Director, Center for Railway Earthquake Engineering Research
Research Area: Earthquake Engineering