Earthquake Countermeasure Technology for Small to Huge Earthquakes

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In the field of railway earthquake countermeasures, earthquake resistant design, aseismic reinforcement, etc., are implemented before earthquakes. On the other hand, measures such as earthquake early warning, operational restrictions, are implemented after earthquakes. Pre-and post-earthquake measures are generally combined to strike a proper balance. Though the targets of these countermeasures are primarily large earthquakes, there is a pressing need for new countermeasures for small earthquakes, such as rapid resumption of operations after small earthquake. This paper describes recent advances in the development of countermeasures for small earthquakes that occur more frequently as well as those for large and huge earthquakes for which some issues are still pending.

Keywords: resilience, strength and recovery, small to huge earthquakes

1. Introduction

Earthquake countermeasures are extremely important for Japan, where the frequency of earthquake occurrence is high. In cases where earthquakes of a certain magnitude are generated, railway functions temporarily decrease, after which functions are recovered. As such, the dual approach of prevention of functional decline immediately after an earthquake and subsequent rapid recovery of functionality is necessary in order to improve the resilience of railways to earthquakes. This concept is shown in Fig. 1. Here, we define “strength” as the performance needed to prevent the decrease in functionality and “recovery” as the capacity to rapidly recover functionality. Precautions such as the assurance of aseismic performance of structures and attached facilities and prevention of the derailment or detachment of tracks or vehicles are needed for improving strength. Additionally, rapid countermeasures such as those based on earthquake early warnings, first response due to rapid damage assessment or re-operation decisions, planned / strategic recovery and restoration countermeasures, and the application of recoverable structures are needed for improving recovery.

The prevention of functional decline following an earthquake and the subsequent functionality recovery process shown in Fig. 1 are generally applicable regardless of the magnitude of the earthquake. However, the importance and specific content of each countermeasure

changes according to the level of shaking strength. For example, in small earthquakes where no damage occurs, the strength of railways against earthquakes is dependent on the content of operational restrictions, and the subsequent recovery is dependent on the time elapsed until operational restrictions are lifted. Of the recently generated small earthquakes, one example that has had a large influence on railways is the Northern Osaka Prefecture Earthquake (Mj = 6.1) on June 18, 2018. With the exception of some regions near the epicenter, railway damage due to shaking was limited, but there were many cases where safety checks of facilities by railway operators forced operations to remain suspended for prolonged periods of time before operations could be resumed [1], which was reported as a social issue.

Generally, the relationship between earthquake magnitude and occurrence frequency is known to follow the Gutenberg-Richter law, and occurrence frequency increases by approximately 10 times on average when the magnitude decreases by one. In other words, there is a considerably higher frequency of small earthquakes than of major earthquakes. As such, it is difficult to make light of small earthquakes in a present society where societal expectations regarding railway safety are very high. However, the current state is such that there are still not very many countermeasure technologies that address railway strength and recovery against these types of small to large earthquakes.

The importance of the impact of large and massive earthquakes is self-evident. In the same way that new issues and findings have been identified with each large earthquake, there has been a significant degree of progress in analyzing and developing countermeasure technologies for these phenomena, and in turn there have been amendments to aseismic design standards, aseismic reinforcement of existing structure, and countermeasures for vehicle derailment / deviation prevention. Additionally, there has been continuous progress on soft-side countermeasures such as earthquake early warning applications and functionality expansion. These countermeasures are thought to ensure a sufficient level of railway strength and recovery against large earthquakes. However, there is still room for improvement, for example with regards to coun-

Fig. 1 Changes in railway functionality during an earthquake

termeasures against phenomena that accompany large earthquakes, such as fault displacement and tsunamis; and countermeasures relating to the assurance of structural safety against tremors that exceed expectations.

With the above issues in context, I think that future earthquake countermeasures for railways will take the form of a balanced response that ensures a proper response against small, large, and massive earthquakes in order to further improve railway resilience. The present text will view earthquakes by magnitude to contextualize and provide summaries of the countermeasure technologies that have been under research and development for each earthquake magnitude.

2. Countermeasure technologies for small earthquakes

This section presents technologies that help effective inspection decision-making and streamline inspections for small earthquakes.

2.1 Damage Information System for Earthquake on Railway (DISER)

As mentioned in the previous section, an urgent issue for railway operators is the early-stage recommencement of railway service in response to small earthquakes, which have a high frequency of occurrence. Generally, once earthquake tremors exceed a set value, temporary operating restrictions are introduced. Afterwards, safety checks are conducted with inspections and services are resumed. With small earthquakes, where the possibility of structural damage is low, the effective confirmation and prioritizing of inspection points strongly influences early-stage resumption of railway services, but then the Damage Information System for Earthquake on Railway (DISER), managed by Railway Technical Research Institute, was developed [2]. This system takes the earthquake motion indices recorded by K-NET at the National Research Institute for Earth Science and Disaster Resilience, uses subsurface information databases, and estimates the tremors on railways using a method to evaluate subsurface amplification which can in turn evaluate the plastic deformation of the ground, and

Fig. 2 DISER analysis process

Fig. 3 DISER display example

a spatial interpolation method. Furthermore, the system uses estimated tremors and a database of structures to estimate structural damage rankings from damage estimate nomograms (Fig. 2). An example of the displayed estimate information is shown in Fig. 3. The spatial mesh size when tremors are estimated is 500 m. The tremor estimation error is about 0.58 for seismic intensity, and tremor information can be transmitted approximately 8-9 minutes after the occurrence of an earthquake [3]. This system has been in operation since August 2019.

2.2 Displacement sensor for bearings

DISER, mentioned in the previous section, estimates structural damage rankings based on earthquake information from public institutions, but it is thought that more effective inspection decisions could be achieved by combining this type of estimated information with information that is directly measured in weak spots. For example, bridge bearings are often located high up, and this typically requires additional time for inspection. If these inspections can hypothetically be conducted remotely, this would greatly reduce the time needed for inspection. Displacement sensors were developed to directly detect damage of bearings in order to address these issues. The developed displacement sensor system composition and a setup example are shown in Fig. 4.

This sensor is capable of detecting displacements in

Fig. 4 Displacement sensor system composition and setup example

rubber pad and steel support members at a horizontal and vertical resolution of 1 mm and 0.3 mm, respectively, without any contact. The performance of the above-mentioned resolution is sufficient considering that displacement confirmation is typically conducted visually. Additionally, since this sensor is capable of transmitting information through a network, work at higher locations can be avoided, and measurement values can be remotely confirmed. Furthermore, these sensors can be continuously used for eight years with a battery, and thus have low maintenance costs. Application of these sensors should help reduce inspection times: investigations and application of the method to real structures are in progress.

3. Countermeasure technologies for massive earthquakes

This section introduces technologies to respond to tsunamis and fault displacements that accompany large earthquakes, as well as those designed to respond to phenomena that exceed expectations.

3.1 Rapid prediction of tsunami inundation areas

Tsunamis are phenomena that accompany large earthquakes. The tsunamis from the 2011 off the Pacific Coast of Tohoku Earthquake caused massive damage to railway facilities. The tsunami inundation area is an important piece of information when considering tsunami damage to railways, but these inundation areas change according to fault locations and scale of the generated earthquake and its fault rupture mechanism, so it has been difficult to obtain highly accurate information regarding tsunami inundation areas from epicenter information alone immediately following an earthquake. However, the national institutes of Japan have established large-scale earthquake / tsunami observation networks for the Japan Trench, Nankai, and Tonankai areas, and tsunami wave heights can now be observed in real-time with hydraulic gauges.

A method was developed that rapidly predicts tsunami inundation areas using tsunami wave information, which is measured in real-time, in order to estimate the damage of tsunamis on railways immediately after the occurrence of an earthquake [4]. This method estimates tsunami waves in coastal regions in a short period of time by first

combining tsunami wave information observed in the sea areas near the epicenter and the tsunami transfer function. Next, the estimated tsunami wave height near the coastal area and the tsunami map groups calculated beforehand are matched in order to predict inundation areas in a short period of time (Fig. 5). It is thought that tsunami inundation areas can be accurately predicted immediately following the occurrence of an earthquake with this method, and its accuracy and timing effectiveness have been confirmed by comparing detailed simulation results and the predicted results from our method. The inundation area map groups created with this method can also be used to inform pre-tsunami countermeasures.

3.2 Fault displacement evaluations and countermeasures

The Nobi Earthquake that occurred in 1891 generated fault displacements on the ground surface with a maximum of 8 m and 2 m on the horizontal and vertical directions, respectively. Additionally, the 2016 Kumamoto Earthquake created horizontal fault displacements of up to 2 m. Railway structures can be affected by fault displacements depending on the positional relationship between the railway and the fault. For these reasons, it is important to appropriately evaluate the influence of fault displacements on railway structures and to develop technologies that minimize these influences.

With the above-mentioned factors in mind, methods are now being developed to accurately evaluate fault displacements which occur in the surface layer, and investigating intersection angles and structural types which are minimally influenced by fault displacement. The accompanying featured article on this issue can be referred to for evaluation methods on fault displacement. Investigations have been carried out both on strike-slip and dip-slip faults for determining structural types that are minimally influenced by displacement. Results showed that for side-slip faults, the intersection angle with the fault has a large influence on the structure, and reducing this angle to below 90 degrees can limit damaged areas to only the span of the intersecting area [5]. Additionally, for dip-slip faults, a structural type where overhanging one-span rigid-frame viaducts are linked (Fig. 6) was effective in reducing material damage from fault displacement relative to multi-span rigid-frame viaducts [6].

Fig. 5 Summary of rapid prediction of tsunami inundation area

Fig. 6 Effective structural type for dip-slip faults

3.3 Controlling collapse direction for improving anti-catastrophe performance

The “anti-catastrophe” concept of preventing destructive damage even in cases where seismic activities exceed expectations due to massive earthquakes was introduced in aseismic design standards in 2012. Recently, two methods have been investigated for realizing these concepts from a structural standpoint. One is a dead-weight compensation mechanism, and the other is controlling the collapse direction. The former is explained further in this current issue, so we will focus on the collapse direction-controlled structure [7] here.

The collapse direction-controlled structure concept and a specific structural type example are shown in Fig. 7 (a) and (b). This method is applicable to rigid-frame bridges and viaducts where the structure must not impact residential areas or block emergency supply routes and to worst-case scenarios where the structure collapses. The proposed structure has a block placed between the elevated bridge slabs and columns in order to achieve these objectives. The height of the block is generally set at the same level as the plastic hinge of the column. This structure has demonstrated overall functionality through shake table tests and analyses.

Fig. 7 Collapse direction control concept and structural type example

4. Conclusions

Investigations were carried out to ensure that there are no temporally or discipline-based gaps in the work undertaken to improve railway safety against earthquakes: advances include precautionary countermeasures, countermeasures in the wake of disasters (rapid countermeasures, initial response, restoration / recovery), hard countermeasures, and soft countermeasures. Recently, issues relating to small earthquakes, which occur much more frequently,

have been receiving greater attention, therefore research and development was planned and carried out focusing on earthquake magnitude.

Many of the earthquake countermeasures for railways are designed primarily for massive earthquakes. These countermeasure techniques are of course effective for small earthquakes, but more effective response can be achieved by focusing on issues that are specific to these smaller-scale earthquakes. Additionally, it is thought that overall railway safety can be improved by expanding the scope of phenomena of interest, for example by focusing on countermeasures for phenomena other than tremors which accompany massive earthquakes, and countermeasures for unexpected phenomena.

Multi-faceted responses are essential for improving the resilience of railways to earthquakes. I will keep on pursuing research and development following this wider perspective in order to achieve a safer railway system.

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