The Role of the Center for Railway Earthquake Engineering Research and Recent Research into Earthquake-related Technology

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The Railway Technical Research Institute opened the Center for Railway Earthquake Engineering Research on April 1, 2014 amid increasing concern about the risk of seismic disasters caused in particular by massive earthquakes. Violent earthquake disasters are becoming more common and more complex. In order to achieve safer railway systems able to cope with these conditions, the center was established as a unique “base” for railway-seismic technology in Japan. The center also integrates RTRI’s research resources on quake-motion, seismic design and countermeasure, and early warning. This report introduces the role of CREER and recent research into earthquake-related technology.

Keywords: Center for Railway Earthquake Engineering Research, seismic safety margin, anti-catastrophe

1. Introduction

It was after the Nobi Earthquake in 1891 that a scientific study on the seismic resistance of structures was introduced in Japan, and practical seismic design was introduced after the Kanto Earthquake in 1923. The railway industry was not an exception: The Construction Bureau of the Ministry of Railways enacted the standard design of bridges in 1930, which introduced the requirement for “a horizontal seismic coefficient of 0.2 to be considered for dead weight as seismic action,” a design method also known as the “seismic coefficient method.” Each earthquake has provided new lessons to learn, and the seismic coefficient method was modified little by little and has long been used as a basis for seismic design. Dramatic progress was made following experience drawn from damage to railway structures after the Hyogo-Ken Nanbu Earthquake in 1995, and ever since then, various seismic technologies have been proposed and contributed to the promotion of countermeasures. Aside from structural measures, an earthquake early warning system was also introduced to detect earthquake within seconds, issuing warnings to slow down or stop trains, as appropriate. The first-generation earthquake early warning system, or ‘UrEDAS’ (Urgent Earthquake Detection and Alarm System), was introduced when the Seikan Tunnel was opened in 1988. This UrEDAS could only display, on the command line, information about where the earthquake had originated. Subsequently, the UrEDAS was modified, and a new UrEDAS with a warning issuing function was placed into service for the first time in the world when the Nozomi trains on the Tokaido Shinkansen line were inaugurated in 1992. A compact version of the UrEDAS with a modified preliminary tremor detection function was introduced for the opening of the Hokuriku Shinkansen in 1998. Then, most recently, it was replaced in 2004 with the existing system with a modified algorithm.

It was against this background that Japan was struck by the 2011 off the Pacific coast of Tohoku Earthquake, which was Japan’s largest-ever earthquake. Its moment of magnitude (Mw) was 9.0, and the Earthquake was a sharp reminder that the risk of “unprecedented” disasters still remained.

The Central Disaster Management Council then set a provisional scale value for the largest class of anticipated consolidated earthquakes and tsunamis along the Nankai Trough, of Mw 9.0. They also declared that shakes with intensities of between upper-6 and 7 on the Japanese seven-stage seismic scale should be generally expected over a large area and it has been announced publicly that the probability of a massive earthquake of Mw 8 or more striking over the next 30 years, is 60-70 %. It is now strongly expected that railways and other relevant utilities will prepare for such large earthquakes, based on these forecasts.

At the same time, damage caused by huge earthquakes is affecting wider and wider areas and becoming more complex. For instance, the focal region of the 2011 off the Pacific coast of Tohoku Earthquake and the assumed focal region of earthquakes along the Nankai trough are 400 kilometers or more in length, affecting the whole of Japan. Moreover, cases such as the derailment of a Shinkansen train at the time of the Mid Niigata Prefecture Earthquake in 2004 and damage of catenary poles in the 2011 off the Pacific coast of Tohoku Earthquake are a sign that structures and rolling stock, catenary poles, etc. are part of an integrated system which can lead to complex damage in case of disasters.

In order to cope with such huge earthquakes and build safer railway systems, the Railway Technical Research Institute ( "RTRI") opened the Center for Railway Earthquake Engineering Research ("CREER") on April 1, 2014, to "integrate" RTRI’s research resources in earthquake engineering and serve as Japan’s only “base” for railway earthquake engineering. This report introduces the activities and roles of the CREER and recent developments in the field of earthquake related technologies.
Table 1 Organization of Center for Railway Earthquake Engineering Research

| Research department                          | Description of research                                      |
|----------------------------------------------|-------------------------------------------------------------|
| Seismic Data Analysis                        | Earthquake early detection, and associated issues           |
| Soil Dynamics and Earthquake Engineering     | Issues related to ground behavior, such as seismic ground motion and liquefaction |
| Structural Dynamics and Response Control     | Issues related to seismic response, and seismic isolation and vibration control of structures, vehicles, electrical poles and other equipment. |

2. Activities of CREER

2.1 Activity policy

Various types of earthquake-related research and development have been undertaken by several divisions in RTRI. However, in order to achieve higher quality and accelerate cutting-edge research aimed at seismic risk reduction and better railway resilience research resources were integrated into CREER, to concentrate earthquake related research. Current research and development at CREER includes (1) constructing an earthquake disaster simulator for railways; (2) measures to improve safety against huge earthquakes; (3) earthquake early warning systems; (4) development of new simulation technology; (5) catenary pole protection and vehicle running safety during earthquakes (in collaboration with the associated Technology Divisions); and (6) technological support for seismic design. In addition CREER plans to address other topics in future including i) earthquake risk management and ii) phenomena accompanying an earthquake, such as tsunamis and surface faulting.

At the same time, CREER is continuing to play its role as central “base” for railway earthquake engineering, by engaging in work such as: (1) actively providing information related to earthquakes; (2) serving as a disaster recovery base when earthquakes occur; and (3) fostering and training railway engineers who can put into practice and deploy earthquake disaster risk-reduction technology. As for (1), the earthquake information distribution system, began operation in June 2015 and details of this system are described in Chapter 4.

2.2 Organization

CREER consists of three research departments: Seismic Data Analysis, Soil Dynamics and Earthquake Engineering and Structural Dynamics and Response Control each working in the fields listed in Table 1, respectively, except for seismic design and seismic risk assessment which are cross-cutting themes and addressed by all the departments together.

3. Recent research and development

3.1 Seismic design and anti-catastrophe

How to respond to unprecedented and unanticipated crises (earthquakes) became a social concern after the 2011 off the Pacific coast of Tohoku Earthquake. Seismic resistance standards therefore require designs to assume the occurrence of an earthquake on an unanticipated scale, and ensure that measures are in place to prevent such an earthquake causing catastrophic damage, while at the same time providing means to enable a rapid recovery of functions in the whole system[1]. This concept is called “anti-catastrophe.” Figure 1 shows the relationship between conventional seismic design and “anti-catastrophe” design. In the seismic design process, designing and checking are carried out so as to ensure safety and restorability against the L1 and L2 design earthquakes. On the other hand, “anti-catastrophe” is to consider a phenomenon uncontrollable with seismic design and take into consideration nonstructural measures including structural planning, in addition to the structural measures. It is essential to reinforce the seismic design and seismic retrofit and improve seismic safety margin. However, it is impossible to reduce the part of a complementary set for the seismic design to complete zero however we may reinforce it. Both the “improvement of seismic safety margin” and “improvement of anti-catastrophe” through seismic design are required to minimize the damage from huge earthquakes.

Fig. 1 Relations between Seismic Design and Anti-catastrophe Design

3.2 Recent research and development to enhance seismic safety margin

The first thing to do in order to enhance seismic safety margin is (1) accurate predicting of the seismic motions
and structures’ behaviors through high-precision simulation. Seismic design and retrofitting of structures will be conducted after that. Taking viaducts as an example, the following specific techniques are required against scenario earthquakes: (2) techniques to keep structures (columns) from collapsing; (3) techniques to restrain the responses of structures; and (4) techniques to prevent derailment as much as possible. The RTRI has proceeded with development of the above listed techniques.

The techniques to keep columns from collapsing in a scenario earthquake include techniques to (i) increase member thickness; (ii) cover members with reinforcing material; (iii) add members; and (iv) apply high-performance material, among which, reinforcement with steel jacketing, which falls under item (ii), is the most proven reinforcing technique in the Japanese railways, which was developed to prevent shear failure and improve deformation performance. The reinforcement with steel jacketing was applied to viaduct columns and intermediate columns of cut-and-cover tunnels, which have a lower shear capacity compared to flexural capacity. This measure was applied mainly on Shinkansen tracks as a priority, under the guidance of the Ministry of Land, Infrastructure, Transport and Tourism.

Structural response restraining techniques include the development of various vibration control devices and seismic isolation devices. Though methods have been developed in architecture and for road bridges, RTRI is now working on negative stiffness friction dampers as a means to enhance seismic isolation (Fig. 2) [2]. In this device, a damper with negative stiffness is built into seismic isolation bearings to further decrease stiffness and lengthen the natural period of the structure, while the friction damper also adds damping.

Super-continuous footing is another recent development, where footing is made continuous over several hundred meters[3]. Figure 3 shows a conceptual diagram of this product. Larger footing should increase bearing capacity and thereby the need for pile foundations or at least reduce their quantity or length. Since this system also reduces and equalizes the effective input at each foundation point, the responses of the viaducts are also equalized and reduced. The action of this measure improves the performance in terms of resistance of both catenary poles and trains running safety on viaducts.

3.3 Recent research and development to improve “anti-catastrophe” performance

The techniques to improve anti-catastrophe performance can include: (1) structural measures; (2) earthquake early warning; (3) virtual scenarios and drilling; and (4) development of nonstructural measures, such as evacuation guidance.

(1) Structural measures to improve “anti-catastrophe” performance

One of the worst cases to be avoided in the railways, is complete collapse of a structure which is likely to produce casualties. The “dead weight compensation mechanism” is a structural measure against such a crisis [4]. The dead weight compensation mechanism means that should column members supporting a structure be destroyed in an earthquake exceeding anticipated scale, the dead weight at least is supported and preventing the structure from collapsing. The rigid-frame viaduct in Fig. 4, is a proposed design using the dead weight compensation mechanism. It consists of two types of member: (i) normal members built to resist seismic force (the columns in light blue in
the normal members be destroyed by an unanticipated earthquake, to prevent the structure from collapsing (dead weight compensation members shown in pink). The normal members are designed according to conventional seismic design, while the dead weight compensation members are part of a structure which is not exposed to loads caused by seismic force and thus do not undergo any stress, even if subjected to unanticipated seismic force, thereby remaining undamaged. The dead weight compensation members are designed according to conventional seismic design, while the dead weight compensation members are part of a structure which is not exposed to loads caused by seismic force and thus do not undergo any stress, even if subjected to unanticipated seismic force, thereby remaining undamaged.

(2) Upgrading of earthquake early warning system

Of the worst cases scenarios to be avoided are a train derailing at high speed due to violent seismic motion, or a train colliding with a damaged or collapsed structure, which would both lead to heavy casualties. Earthquake early warnings are an effective means to prevent these events happening by detecting earthquake motion as early as possible, and issuing a warning before structures being to vibrate violently, allowing the train to either slow down or stop immediately. Earthquake early warning systems today estimate the epicentral distance from the growth in initial P-wave acceleration for 2 seconds (B-Δ method). The magnitude of the seismic motion is then calculated from the estimated epicentral distance and the observed displacement amplitude, using a distance attenuation formula (Fig. 5).

In order to improve “anti-catastrophe” performance RTRI is currently working to (1) give more accurate and (2) earlier warnings, and has developed a new C-Δ method as algorithm to replace the B-Δ method to achieve these objectives, where the epicentral distance is estimated using the growth of initial P-wave acceleration for approx. 0.5 second and approximating it using the linear function shown in Fig. 5. This new method has improved the accuracy in estimating epicentral distance by approx. 13% and reduced the data length for estimation to 0.5 seconds from the conventional 2-seconds.

In order to issue even earlier warnings, RTRI is also examining the use of (i) seafloor observation network data for earthquakes and (ii) underground seismographs. For subduction-zone earthquakes, using ocean-bottom seismometers can increase the time allowance significantly. Some organizations, including the National Research Institute for Earth Science and Disaster Disaster Simulator

In order to avoid worst case scenarios, drilling, or “virtual practice” is required, through mental preparation imagining what could happen if an unanticipated phenomenon occurred. However, drilling and virtual training based only on past findings and experiences, makes it difficult to prepare for events, which by definition exceed expectations. Therefore, RTRI is currently constructing an “Earthquake Disaster Simulator” which will be used a tool to support this virtual training (Fig. 6).

This simulator can reproduce an earthquake on an arbitrary scale at an arbitrary location and, in case of an occurrence of such an earthquake, enables analysis of seismic wave propagation at that level across the whole of Japan, while also analyzing the behavior of the surface ground and structures for a section stretching across several hundred kilometers. The analytical results are displayed in realistic fashion to facilitate virtual training of users, in a way which stretches their imagination.

4. Earthquake information distribution system

CREER has developed a system to rapidly integrate strong earthquake data records, released to the public by public institutions, into RTRI, to perform calculations using the data, such as maximum acceleration distribution on the surface of the ground and SI values, in order to provide, just a few minutes after an earthquake, information about seismic motion along the railway route, and deploying data corresponding to railway routes. Figure 7 shows the conceptual diagram of the system, which considers ground and structural conditions to make the estimation more accurate, and can also forecast damage to structures. It is hoped at CREER that this system will contribute greatly to faster recovery of train operation and resuming of services.
5. Conclusion

Railway systems are part of the foundation of social and economic activity, and must be able to withstand violent earthquakes which may occur in the future. CREER’s aim as an earthquake research base, is therefore to contribute to this resilience, both through research and development and its other activities.

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