Improvement of Anti-catastrophe Performance — Measures for Unanticipated Earthquake —

Yoshitaka MURONO

Center for Railway Earthquake Engineering Research

How to respond to unanticipated earthquakes has become a concern in Japan after the 2011 off the Pacific coast of Tohoku Earthquake. Seismic design standards for railway facilities therefore need to assume that earthquakes on an unanticipated scale may occur, and should be able to prevent such events causing catastrophic damage. This concept is called “anti-catastrophe.” Thus, in addition to conventional “improvement of seismic performance,” it is necessary to improve “anti-catastrophe” performance to minimize damage from huge earthquakes. This paper introduces some techniques to improve anti-catastrophe performance.

Keywords: center for railway earthquake engineering research, seismic safety margin, anti-catastrophe

1. Introduction

The off the Pacific coast of Tohoku Earthquake, along the Pacific coastline of Sanriku, occurred on March 11, 2011. It was the largest earthquake ever recorded in Japan, with a moment magnitude of 9 on the scale representing the size of earthquakes. The earthquake caused serious damage across the whole of the East of Japan, from Tohoku to the Kanto area. This experience was a sharp reminder of the remaining risk of “unanticipated” earthquakes. Since there are concerns about the occurrence of similar huge earthquakes in the future [1], it is critical for society to be resilient enough to weather such hazards. This “resilience” means ability to remain intact and recover from any natural disaster, including earthquakes, like a reed which bends but does not break, should systems come to a stop [2]. In the case of earthquakes, better resilience requires having both the “strength to withstand a major earthquake” and the “flexibility to recover immediately in the wake of a disaster or catastrophe.” Figure 1 shows a conceptual illustration of this notion.

A key ingredient to enhance “strength” against earthquakes, is being prepared. This implies designing and constructing earthquake-proof structures or seismic retrofitting existing structures.

There are two ways to enhance the “speed of recovery”: preparedness and post-event response (responses in an emergency/immediate reaction, for continuity, restoration and recovery). As such, *anti-catastrophe* design is central to preparedness. The concept of anti-catastrophe design and performance was a notion first defined in the 2012 revised version of the Design Standards for Railway Structures and Commentary -Seismic Design- (hereinafter referred to as “Seismic Design Code”) [3], and was described as further “means to avoid catastrophic situations in case of unexpectedly large earthquakes”, above and beyond basic safe design. Taking tsunamis as an example, seismic design means design and construction of a tall tide embankment, and anti-catastrophe performance means adding an

evacuation structure on the assumption that there may be a remote possibility that a tsunami that exceeds the height of the embankment. In terms of “immediate response in an emergency,” examples include raising an alarm before strong seismic ground motion arrives to ensure evacuation and safety of users and employees. An earthquake early warning system has been developed and installed, to this end, for railways and is in practical use [4]. “Response to ensure continuity” means initial responses including a patrol program, a recovery program and a personnel/material procurement program, where high quality information on the magnitude of shaking and the degree of structural damage is indispensable immediately after an earthquake. One of the tools for that purpose is the “Earthquake Information Distribution System for Railways” that RTRI started operating in June 2015 [5]. This system, which estimates shaking along the railway only a few minutes after an earthquake and outputs information, is expected to be used for resumption of operations and patrolling for inspection. “Restoration and recovery” means actual restoration work.

Seismic design, seismic retrofitting and earthquake early warning systems have been covered quite extensively and are therefore omitted from this report. The focus in this paper is “anti-catastrophe” performance, and introduces RTRI efforts aimed at enhancing anti-catastrophe performance.

Fig. 1 “Strength” and “Restorability” against huge earthquake

2. Anti-catastrophe

The Seismic Design Code defines the L2 design earthquake motion as “the maximum earthquake motion.” However, the Seismic Design Code states that it is not the maximum possible physical earthquake motion, and setting should be based on advanced engineering judgment [3].

Furthermore, the Seismic Design Code does not deny that earthquakes exceeding L2 should be considered in design. How to respond to such unanticipated earthquakes has become a matter of significant concern after the 2011 off the Pacific coast of Tohoku Earthquake. The Seismic Design Code does not deny the possibility of the critical stage considered in design being exceeded but requires some “consideration” for such unexpected circumstances. That is what is meant by “anti-catastrophe.” To explain anti-catastrophe requirements a little more clearly, Fig. 2 illustrates the relationship between conventional seismic design and anti-catastrophe. Seismic design aims to ensure performance meets safety and restorability criteria for the earthquake motion specified in the design requirements. Anti-catastrophe complements these requirements to provide for events that cannot be controlled by seismic design. Anti-catastrophe includes structural planning and other conceptual measures, in addition to the structural design.

In order to minimize damage from massive earthquakes, it is essential to reinforce seismic design and carry out seismic retrofitting as much as possible, similar to what has been done until today. It is impossible however based solely on adding reinforcement to existing seismic design to reduce damage to zero. Maximum prevention of damage can only be achieved through “improvement of seismic safety margins” through seismic design and “improvement of anti-catastrophe performance.”

Fig. 2 Relations between seismic design and anti-catastrophe design

3. Towards improvement of anti-catastrophe performance

Improvement of anti-catastrophe performance does not simply mean assuming earthquake motion several times larger than in the design requirement and then providing a structure with a higher safety factor. It also involves assessing the relative cost of building to these higher specifications. For example, in Fig. 3, the structural properties of a bridge pier and construction costs change as estimated seismic action is increased. Figure 3 shows that that when seismic action doubles, the sectional area of the pier is about 1.7 times larger than the original area. Since girder construction accounts for a large percentage of the total construction cost as shown in Fig. 3, the graph indicates that the total construction cost would therefore increase by

Fig. 3 Relations between scale of assumed earthquake and construction cost

approximately 30 % if the assumed seismic motion is doubled, based on the relationship between the design seismic force and cost which are not on a one-to-one ratio. In case of a rigid frame viaduct, the sensitivity of the relationship is even greater. Consequently, conventional seismic design based on assuming larger and larger earthquake motion and designing a structure which can withstand this, will lead to a constant increase in cost, which is not realistic. Furthermore, it is not possible to say exactly how many times greater earthquake motion will be in an earthquake, which is by definition, unanticipated. As such, it is hard to judge when anti-catastrophe has been fully considered. Figure 4 illustrates the purpose of ‘anti-catastrophe’ design, in relation to normal seismic design: the idea is to keep damage below the level expected under normal seismic design, even when seismic motion exceeds the scale anticipated in normal seismic design requirements.

Therefore, to improve the anti-catastrophe, aside from the physical measures described below in Chapter 4, there are also design methods which can be applied. A first step for example is to avoid disasters in the first place by taking preemptive measures. Although many factors including socioeconomic aspects should be considered in determining a route plan, building away from active faults is one way of enhancing anti-catastrophe. Another way to

Fig. 4 Technologies to improve anti-catastrophe performance

improve resilience is to consider the surrounding environment of the structure in terms of restorability, during the design phase [3]. More specifically, experience from past earthquakes shows that the state of side roads leading to a viaduct and under-viaduct areas greatly affect rebuilding and repairs after seismic damage, therefore possible measures to improve resilience could include “securing access to structures and work yards” and “ensuring points on the structure most vulnerable to damage are located in positions where inspection or repairs can be easily conducted.”

4. New technologies to improve anti-catastrophe performance

This chapter discusses the physical measures to improve anti-catastrophe performance, including those introduced after the Seismic Design Code was published. Resilience can be improved by identifying and taking measures to avoid “catastrophes that must absolutely be avoided,” even in unanticipated circumstances. In 2014, for instance, the Japanese Government adopted the Fundamental Plan for National Resilience [6] which sets out four fundamental goals to be achieved, and proposes an “Action Plan for National Resilience 2014” [7] to avoid worst case scenarios that should never happen. These include various cases including high numbers of casualties due to large-scale and multiple collapse of buildings and transportation facilities.

4.1 Example 1: Existing technologies to improve anti-catastrophe performance (Control of failure mode)

A scenario where railway structures collapse and cause casualties in an unanticipated earthquake can be considered a catastrophe [7]. Moderating the process leading to structural failure is a measure to prevent this kind of catastrophe. This is why the Seismic Design Code prescribes structural designs made to avoid brittle fractures, i.e. ensuring that structures have a flexural failure mode [3].

4.2 Example 2: Dead weight compensation mechanism

The “dead weight compensation mechanisms” are more powerful measures aimed at preventing disasters due to structural collapse. The dead weight compensation mechanism prevents structures from complete collapse by protecting against the loss of their vertical support, from collapse of vertical members, such as columns or piers in an earthquake of unanticipated magnitude. Figure 5 shows the mechanism applied to a viaduct. The structure consists of two types of columns: one set are called “normal members” (the columns shown in light blue in the figure), and

Columns serving only to support the dead weight in case normal columns, designed to resist seismic loads, are destroyed (dead weight compensation columns)

Fig. 5 Rigid-frame viaduct with dead weight compensation mechanism

the other set are “dead weight compensation members” (the members shown in pink). The normal members are conventional columns designed to satisfy seismic performance requirements against an L2 earthquake. The dead weight compensation members bear only vertical loads and are designed with a device which avoids any horizontal load being exerted by seismic force and therefore they do not bear any stress, even if subject to unanticipated seismic force, allowing them to remain undamaged. Consequently, if the normal members are destroyed by an earthquake of unanticipated magnitude, undamaged dead weight compensation members remain and can support at least the superstructure.

The design of a rigid-frame viaduct with one layer and five spans, with ten columns, was estimated [8]. Estimation results showed that if four out of ten of the columns were changed to dead weight compensation members, this would cause an increase in the seismic inertial force that the normal members would have to bear in an L2 earthquake. However, the bearing capacity of these normal columns would only have to be increased with a few tensile reinforcements (Table 1), while the four compensation members could then prevent collapse of the superstructure in case of unexpectedly violent seismic action.

4.3 Example 3: Mechanism to control the direction in which structures collapse

It is also important to predict and take measures against the know-on effects and consequences of earthquakes of unexpected magnitude, including human casualties, or damage to structures which leaves them beyond repair. One such measure is to introduce mechanisms which control the direction in which structures may fall or mechanism to control the spread of the collapse (joint research with Prof. Masato Saito of Saitama University) (Fig. 6). Details of these mechanisms are described in relevant literature [9], but briefly, methods include securing critical routes for pedestrians, the users of surrounding

Table 1 Example of estimation for designing dead weight compensation structure

Structure type	Reinforcing Steel arrangement of normal members	
	Tensile reinforcements	Lateral ties
Conventional seismic structure	D32 × 5pcs.	D19-1set-150ctc
Dead weight compensation structure	D32 × 7pcs.	D19-1set-100ctc

Note: The dimensions of a column are 0.85 m by 0.85 m, and its height is 5.5 m.

Fig. 6 Control of collapse directions

facilities and emergency transportation roads for recovery operations in the wake of a disaster and dedicated roads and spaces for enable repairs and rebuilding of structures. Ultimately, these measures contribute to improving anti-catastrophe performance.

5. Conclusion

Railway systems are the backbone of socioeconomic activity, and are expected to be resilient against massive earthquakes which may occur in the future. Although there are various ways to improve resilience, this report introduces physical measures focused on increasing anti-catastrophe. Together with the earthquake early warning system, these disaster prevention measures will contribute to raising overall resilience of the railways.

In order to ensure that the proposed physical countermeasures are as effective as possible, it is also important to engage in imagining possible scenarios, or “virtual practice drills” in view of what could happen if an earthquake of unanticipated magnitude occurred. Virtual practice drills or virtual training based only on past findings and experiences, however, make it difficult to prepare for earthquakes that are by definition unanticipated. It is therefore expected that simulators will be a great contribution to overcoming the limits of human imagination, to help solve this problem. The author of this paper, in association with

a team of fellow researchers constructed an “Earthquake Disaster Simulator” as a tool to support virtual practice drills and training [10]. In future, it is hoped that physical and design measures will be integrated enabling comprehensive proposals allowing more targeted measures.

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Author

Yoshitaka MURONO, Dr. Eng.
Director, Center for Railway Earthquake
Engineering Research
Research Areas: Earthquake Engineering,
Seismic Design, Soil-Structure Interaction