Proposal of Evaluation Method for Anti-catastrophe Resistance for Railway Structures

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An active debate began in the wake of the 2011 off the Pacific coast of Tohoku Earthquake about how to deal with the “unanticipated large earthquakes” in terms of seismic design of civil structures. The concept of “anti-catastrophe resistance” was first introduced in the seismic design standards for railway facilities when they were revised in 2012. No method to evaluate the degree of anti-catastrophe resistance was proposed at the time, however, corresponding to the structure planning stage. Therefore, study was undertaken to develop a method to evaluate “Anti-catastrophe resistance.”

Keywords: anti-catastrophe resistance, seismic design, unanticipated large earthquake

1. Introduction

Following the 1995 Hyogo-ken Nambu earthquake, efforts were launched in earnest to further advance the aseismic design of railway structures and seismically retrofit existing structures. These efforts led to a noticeable decline in the number of structures severely damaged in more recent large-scale earthquakes. Figure 1 shows that while the area controlled by aseismic design had been gradually expanding, the 2011 off the Pacific coast of Tohoku earthquake which struck with an unanticipated magnitude (Mw = 9.0) highlighted the fact that this area still had gaps.

Meanwhile, a new performance requirement called “anti-catastrophe resistance” was introduced into the Design Standards for Railway Structures (Aseismic Design Standard) revised 2012 (hereinafter “the Aseismic Standards”) [1], which refers to the characteristics of a structure that prevents it from suffering catastrophic damage even in an earthquake of unanticipated magnitude. A number of measures [2 etc.] have been proposed over the past few years aimed at improving the anti-catastrophe resistance of civil structures. However, the Aseismic Standards do not include any method to quantitatively evaluate the anti-catastrophe resistance of existing structures or to increase anti-catastrophe resistance.

This paper presents a method that has been developed to quantitatively evaluate the anti-catastrophe resistance of structures. The anti-catastrophe resistance of structures can be evaluated and compared using this method. This in turn makes it possible to rationally prioritize structures that require aseismic measures and tailor the action needed on each structure.

2. Development of method for evaluating anti-catastrophe resistance of railway structures

2.1 Outline of the method to evaluate anti-catastrophe resistance

This section discusses the method for evaluating anti-catastrophe resistance. To begin with, two structures can be considered: Structure A, with arterial roads running directly below it, and Structure B, with no arterial roads nearby. How would these two structures compare in terms of anti-catastrophe resistance? Their surrounding conditions and specifications are identical. Structures A and B both would therefore both be rated equally in terms of seismic performance in the light of conventional aseismic design standards. Both of them could collapse in an earthquake of unanticipated magnitude. If Structure A collapsed, the arterial roads may have to be closed. Therefore, Structure A’s performance, factoring in earthquakes of unanticipated magnitude, would be rated lower than Structure B. This is an example of how a change in the evaluation of a structure’s performance could arise by introducing the concept of anti-catastrophe resistance.

Anti-catastrophe resistance evaluation measures how much damage could be avoided in case of a railway disaster including the collapse of structures, etc., that would not normally be anticipated using the conventional aseismic design approach. Specifically, multiplying the impact C, of railway disasters by the catastrophe prevention capability P, provides the magnitude of the preventable catastrophe, or the anti-catastrophe resistance \( R \), as shown by (1).

Fig. 1 Classification of events for consideration in aseismic design
where \( m \) stands for the number of catastrophes that is anticipated in the anti-catastrophe resistance evaluation. \( P \) is a function of the achieved score \( r \) for the structural performance indices that are important in improving anti-catastrophe resistance. Figure 2 shows the steps for evaluating anti-catastrophe resistance \( R \) according to (1). The specific procedure for each step is detailed below.

1) Evaluation of the achieved score \( r \) for the performance indices: Catastrophes are identified (Section 2.2). Performance indices that are important in avoiding those catastrophes are identified (Section 2.3). Each structure is quantitatively evaluated to obtain a score \( r \) for each performance index on a scale of 0 to 1 (Section 2.4).

2) Evaluation of catastrophe prevention capability \( P \): \( P \) is evaluated on the basis of the achieved score \( r \) for each performance index. In the proposed method this is done by using a fault tree where a catastrophe is defined as the top event to calculate the catastrophe prevention capability \( P \) (Section 4).

3) Evaluation of catastrophe’s impact \( C \): The catastrophe is evaluated for the magnitude of its impact \( C \). In the proposed method, a survey is conducted with railway passengers to identify their tolerance levels towards catastrophes (Section 3) and the tolerance values are then subtracted from 100 to obtain the impact \( C \) of the catastrophe.

4) Evaluation of anti-catastrophe resistance \( R \): The results of 2) and 3) are entered into (1) to calculate the anti-catastrophe resistance \( R \).

As discussed above, to achieve the goal of avoiding catastrophes, performance indices are identified for structures as their performance requirements and the achieved score for each of those indices is evaluated for each structure. This follows the same sequence as in ordinary performance design. With unanticipated events, however, it is difficult to set appropriate actions and calculate the response values in the anti-catastrophe resistance evaluation process. Therefore, the achieved scores for performance indices are evaluated not by following such a sequence but on the premise that some of the functions are lost (e.g. structural collapse) (Section 2.4), and this is a major difference from the ordinary design process.

### 2.2 Sampling of catastrophes that should not occur on railways

Sample catastrophes that should not occur on railways, for example, related to structural safety, restorability and safe running of vehicles were thoroughly sampled. One of the references for the identification process was the National Resilience Action Plan [3], which sets forth key policy measures for national resilience. The plan details targets that must be established before major disasters hit as well as worst case scenarios that can hinder the fulfillment of targets and therefore must be avoided. In the study, catastrophes in the railway sector were identified by referring to the plan.

#### Catastrophe I: Threat to Passengers’ life
- Example I-1: Serious passenger casualties (of life-threatening nature)

#### Catastrophe II: Uncontrollable secondary disasters
- Example II-1: Collapse of buildings and casualties around the tracks
- Example II-2: Closure of arterial roads etc.
- Example II-3: Additional damage caused by aftershocks

#### Catastrophe III: Extended delay before service restoration
- Example III-1: Extended delay before railway structures are restored
- Example III-2: Excessive time required for post-earthquake situation assessment taking long

### 2.3 Identification of anti-catastrophe resistance performance indices

Performance indices important for improving the anti-catastrophe resistance of railway structures need to be identified. To do this a fault tree was drawn with one of the catastrophes identified in Section 2.2 as the top event, establishing scenarios leading to the catastrophe. Figure 3 shows an example of this, example I-1 of Catastrophe I mentioned above with scenarios leading to the catastrophe.

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**Fig. 2 Steps for evaluating anti-catastrophe resistance \( R \) of railway structures**

\[
R = \sum_{i=1}^{m} C_i \cdot R(r_i)
\]
As recent earthquakes have not led to any passenger casualties, data was gathered on people severely injured for other railway-related reasons, not just earthquakes. The data gathered has shown that there are three scenarios that can lead to severe casualties: (a) trains deviating far from the tracks, (b) trains crashing into electric poles and other installations and (c) trains falling off structures. Accordingly, the fault tree was arranged in such a way that the top event branched into these scenarios, then down to the causal events. This exercise provided the following conclusions: there was a need to prevent track subsidence due to structural collapse or damage by ensuring structures had sufficient redundancy and robustness, as shown by their performance indices.

For the other types of catastrophe, two possible scenarios were found for examples II-1 and II-2: firstly, the existence of two potential sources of secondary disaster - nearby buildings and arterial roads; and secondly, structural collapse towards these two potential sources leading to a secondary disaster. To avoid these scenarios, the performance indices of structures must not only show sufficient redundancy and robustness, there must also be a sufficient buffer area around these structures to ensure that no buildings or arterial roads lie in the line of structural collapse. In example II-3, structures must have a performance index showing sufficient remaining strength after the main shock (anti-aftershocks). In example III-1, structures must have a performance index showing sufficient individual structural restorability. In all, a total of five performance indices were identified as shown in Fig. 2.

### 2.4 Evaluation of the achieved performance index scores

Each structure is evaluated on a scale of 0 to 1 for the achieved score \( r_1 \) for each of the performance indices identified in Section 2.3. This section only gives an outlines of the evaluation method: details will appear separately. While any railway structure can be evaluated using the method for achieved scores, the following text focuses on Shinkansen viaducts.

Starting with redundancy, the achieved score \( r_1 \) for redundancy is based not on toughness, e.g. improved yield strength through seismic retrofit, but on the criterion of whether or not the structure still retains its function as a structure when a number of its structural members such as piers and beams are damaged. That specifically means evaluating the structure’s dead weight compensation performance relative to the level of damage. Structures with higher dead weight compensation performance regardless of the severity of the damage sustained have higher achieved scores. Redundancy can be improved by, for example, adopting a rigid-frame viaduct with multiple piers or the dead weight compensation mechanism [4] proposed by Nishimura et al. On the other hand, RC bridge columns have an achieved score of zero.

The achieved score \( r_5 \) for robustness is evaluated using a robustness function [5]. As the evaluation considers unexpected events, robustness is measured not based on probabilities of the variation of actions but by measuring the maximum variation in parameters that meet specified constraints in response to the variation of actions.

The achieved score \( r_5 \) for securing of buffer areas around structures is evaluated from the viewpoint of whether or not collapsing structures would cause secondary disasters. If there are no structures or arterial roads in the buffer areas, there will be no secondary disasters when the viaduct collapses, resulting in an achieved score \( r_5 \) of 1.0. On the other hand, if there are structures and arterial roads are present in the buffer areas and are in the line of collapse of the viaduct, then the achieved score \( r_5 \) will be less than 1.0. Structural measures available to improve the achieved score in those areas include collapse direction control devices proposed by Saitoh et al. [6], Toyoooka et al [7]. Those devices are capable of controlling viaducts to prevent them from collapsing towards structures and arterial roads, thus improving the achieved score.

The achieved score \( r_4 \) for anti-aftershocks, or the remaining strength against aftershocks, is evaluated on basis of the remaining rate of seismic performance proposed by Nishimura and Murono [8].

The achieved score \( r_5 \) for structural restorability, the last of the five performance indices, is evaluated based on the rate of utility disruption \( UD = Utility\ Disruption\ ) shown in Fig. 4. Train service is suspended soon after an earthquake and then gradually restored following inspection and recovery phases. The relationship between the time elapsed since the start of restoration effort and the recovery rate can be expressed by a recovery curve \( S(t) \). Passenger satisfaction with train service suspension, or passengers thinking that service suspension is understandable, which stands at nearly
100% immediately after an earthquake, declines gradually with time. The relationship between the elapsed time and passenger satisfaction can be expressed by a satisfaction curve.

The achieved score for structural restorability can be evaluated based on reduction $S$ in transported volume, which is the area between the recovery curve $S(t)$ and the 100% horizontal line of recovery rate when the former is below the 100% recovery rate [9]. In this paper, however, by referring to the method proposed by Nojima et al. [10], the area defined above is weighted by passenger dissatisfaction $A(t)$ and the result is defined as utility disruption $UD$, which can be calculated using (2).

$$UD = \int_{0}^{\infty} (1 - A(t))(1 - S(t))dt$$ (2)

This corresponds to the hatched area in Fig. 4. The achieved score for structural restorability can then be defined as utility disruption $UD$ normalized by reduction $S$ in transported volume, as shown in (3).

$$r_3 = \frac{1 - UD}{S} = 1 - \frac{\int_{0}^{\infty} (1 - A(t))(1 - S(t))dt}{\int_{0}^{\infty} (1 - S(t))dt}$$ (3)

3. Evaluation of impact of catastrophe

There are a number of catastrophes in the railway sector, having varying degrees of impact. A structure that can avoid many catastrophes of low impact cannot be regarded as having high levels of anti-catastrophe resistance. Proper evaluation of anti-catastrophe resistance requires thorough knowledge of the various degrees of the impact of a catastrophe.

The impact of a catastrophe can be measured uniformly in terms of economic loss in monetary terms. However, the catastrophes identified in Section 2.2 cover a wide range of subjects including casualties, decline in transport functions and social loss resulting from secondary disasters. It is currently difficult to use economic loss as a measure to evaluate all types of catastrophe, since this would limit the scope of evaluation to certain types of disaster. Given the above, quantification of impact was attempted in this study based on passenger surveys. In conducting surveys, attention must be paid to eradicate bias intrinsic to any survey. However, the relative ease with which catastrophes that are difficult to quantify with a measure of monetary value can be quantified with surveys, outweighed the concern.

In the survey, railway users were asked to answer the following question by selecting one option out of five that was closest to their opinion. The five options were: Tolerable, Tolerable to a certain degree, Undecided, Intolerable to a certain degree and Intolerable.

Question: Please assume that [assumed earthquake] occurs, causing the following events on the railway. How would you feel then? For each event, select the one among the options that is closest to your opinion.

Note: Any one of the following goes into [assumed earthquake]: seismic intensity 4 earthquake, seismic intensity 5 to 6 (weak), seismic intensity 6 (strong) to 7, earthquake on unprecedented scale.

When answering, four cases of questions were set as the assumed earthquakes. For each level of seismic intensity, the question was presented to 633 persons. With all four levels, a total of 2,532 persons, consisting of four different group of 633 persons with as many different intensity levels, were surveyed. Analytical results from the answers collected are described below. For each of the catastrophes, “Tolerable” and “Tolerable to a certain degree” were taken to indicate the tolerance level while “Undecided” answers were excluded from consideration. The impact of each catastrophe was evaluated based on the tolerance level obtained, as shown in Fig. 5.

The results show that Example I-1, ‘serious passenger casualties’ had the greatest impact while Example III-1, ‘structural restorability’ had the smallest impact, with Examples II-1, II-2 and II-3 of secondary disasters lying in-between. There is no significant difference in impact among the three levels of seismic intensity other than the intensity of 4.

Among the results shown in Fig. 5, those relating to unexpected earthquakes were applicable to this study as its purpose was to study anti-catastrophe resistance to unexpected earthquakes.

4. Quantitative evaluation of the anti-catastrophe resistance of railway structures

This section describes calculations of the anti-catastrophe resistance of a railway structure using the proposed method. The structure in question is a 5-span rigid-frame Shinkansen viaduct with a natural period of 0.5 seconds. The structure’s anti-catastrophe resistance was evaluated for the following three cases.

Case 1: Case 1 basic conditions: a viaduct that does not span roads and with no buildings in close vicinity. Earthquake Early Warning System, derailment prevention measures, deviation prevention measures and vehicle guiding devices are all installed, considering that in reality the early warning system is installed on all Shinkansen routes while other measures and devices have been gradually

![Fig. 5 Evaluation of the impact of a catastrophe](image-url)
installed.

Case 2: Viaduct spanning arterial roads. Other conditions are the same as Case 1.

Case 3: Same Case 2 but viaduct is equipped with the dead weight compensation mechanism [4].

First of all, the achieved scores for each of the performance indices were evaluated using the methods described in Section 2.4. The results of the evaluation are shown in Table 1. The criteria used for the evaluation are summarized below. As mentioned in Section 2.1, the evaluation was made on the premise that the structure was severely damaged.

Achieved score $r_i$ for redundancy: In both Case 1 and Case 2, the rigid-frame viaduct has multiple piers. Based on the relationship between the damage level of those piers and the dead weight compensation performance, $r_i$ was rated at 0.33. In Case 3, as the dead weight compensation mechanism keeps the viaduct from collapsing, $r_i$ was rated at 1.00.

Achieved score $r_2$ for robustness: In Case 3, as the dead weight compensation mechanism keeps the viaduct from collapsing, $r_2$ was rated at 1.00.

Achieved score $r_3$ for securing of buffer areas around structures: In Case 1, as there are no arterial roads around the viaduct, $r_3$ was rated at 1.00. In Case 2 in which there are arterial roads alongside the viaduct but no measures are taken, $r_3$ was rated at 0.00. In Case 3 in which the viaduct has the dead weight compensation mechanism, $r_3$ was rated at 1.00.

Achieved score $r_4$ for anti-aftershocks: In both Case 1 and Case 2, $r_4$ was rated at 0.86 based on the remaining rate of seismic performance resulting from the evaluation of the structural period. In Case 3, the viaduct would not collapse in the main shock but possibly suffer additional damage in aftershocks. Therefore, $r_4$ was rated at the same level as Case 1 and 2.

Achieved score $r_5$ for structural restorability: In both Case 1 and Case 2, $r_5$ was calculated as 0.37 using (3). In Case 3, the dead weight compensation mechanism should prevent bridge collapse and other damage and thus eliminate any need for the girders to be lifted during restoration. This is expected to help shorten the time spent for restoration. In consideration of this, $r_5$ was rated at 0.53.

In the next step, the viaduct’s catastrophe prevention capability was evaluated for each catastrophe based on the achieved scores. In the evaluation of catastrophe prevention capability, each causal event in a fault tree, an example of which is shown in Fig. 3, is weighted to evaluate the weight of the top event. As an example of this, the results of evaluation of the capability to prevent serious passenger casualties are shown in Fig. 6. Performance index-related causal events are weighted by a difference between the achieved score for the index and 1. Events for which weight cannot be determined are assigned 0.50. This provided the following results: in both Case 1 and Case 2, the catastrophe prevention capability $P_i$ was 0.51 while it was 0.75 for Case 3. The same process was repeated for every catastrophe to evaluate the catastrophe prevention capability. The overall results are shown in Table 2. With Example I-1 of serious passenger casualties, the highest catastrophe prevention capability was achieved in Case 3 due to improved redundancy by the dead weight compensation mechanism. With Example II-2 of closure of arterial roads, Case 2, in which there are arterial roads alongside the viaduct but so special measures were taken, achieved the lowest catastrophe prevention capability. With Example II-3 and Example III-1, the catastrophe prevention capability was equal to the achieved score for all cases.

For each case, the catastrophe prevention capabilities were multiplied by the impacts to obtain the anti-catastrophe resistance. The overall results are shown in Fig. 7. While Case 1 and Case 2 would be rated at the same level of performance by the ordinary aseismic design standards, or the conventional aseismic design standards in Fig. 1, these cases have different levels of anti-catastrophe resistance $R$ due to the difference in securing buffer areas around the structure. Also, the figure suggests that structures built according to the ordinary aseismic design only still have certain levels of anti-catastrophe resistance.

Comparison of Case 2 and Case 3 shows an increase in anti-catastrophe resistance achieved by taking relevant measures. However, anti-catastrophe resistance is nothing more than a consideration, a parameter for achieving higher-quality design. Anti-catastrophe resistance is not an absolute measure for evaluation. It is not that anti-catastrophe resistance $R$ must be more than a certain specified value. One of recommended applications for anti-catastrophe resistance is as follows. The anti-catastrophe resistance value for Case 1 where the viaduct is built in a standard location and is used as the reference value. If the viaduct is built in such a way that it crosses arterial roads, its anti-catastrophe resistance value drops to 63% of the reference value. If the viaduct is equipped with the dead weight compensation mechanism, its anti-catastrophe resistance value rises to 116% of the reference value.

| Table 1 | Scores achieved for each case |
| --- | --- |
| **Performance index** | **Achieved score** |
| | Case1 | Case2 | Case3 |
| Redundancy $r_1$ | 0.33 | 0.33 | 1.00 |
| Robustness $r_2$ | 0.11 | 0.11 | 1.00 |
| Securing of buffer area $r_3$ | 1.00 | 0.00 | 1.00 |
| Anti-aftershocks $r_4$ | 0.86 | 0.86 | 0.86 |
| Structural restorability $r_5$ | 0.37 | 0.37 | 0.53 |

Table 2 Evaluation of catastrophe prevention capability $P_i$ and anti-catastrophe resistance $R$

| Catastrophes | Impact $C_i$ | Prevention capability $P_i$ | Anti-catastrophe resistance $R$ |
| --- | --- | --- | --- |
| Case1 | Case2 | Case3 |
| Example I-1: Serious passenger casualties | 75 | 0.51 (38) | 0.51 (38) | 0.75 (56) |
| Example II-2: Closure of arterial roads | 55 | 1.00 (55) | 0.00 (0) | 1.00 (55) |
| Example II-3: Additional damage by aftershocks | 51 | 0.86 (44) | 0.86 (44) | 0.86 (44) |
| Example III-1: Extended delay before structures are restored | 35 | 0.37 (13) | 0.37 (13) | 0.53 (19) |
| Anti-catastrophe resistance $R$ | 150 | 95 | 174 |
5. Conclusion

To improve the resilience of the railways, its structures need to be reinforced against catastrophes. In this study, a method for quantitatively evaluating anti-catastrophe resistance was developed. Specifically, the anti-catastrophe resistance $R$ of a railway structure is evaluated by the product of the structure’s catastrophe prevention capability $P_i$ and the impact of the catastrophe $C_i$.

The following technical elements were used to verify the method for practical application: structural catastrophe prevention capability $P_i$, identification and quantitative evaluation of anti-catastrophe resistance performance indices, and evaluation of the impact of catastrophe $C_i$ through railway passenger surveys. Result of calculations of anti-catastrophe resistance using the method presented in this paper, confirmed that it can quantitatively evaluate anti-catastrophe resistance.

While efforts are expected to continue to develop anti-catastrophe resistance evaluation methods and specific measures to improve the parameters, the proposed method offers a possible direction for such work. The method needs to be refined further for practical application with respect to its overall effectiveness and the sophistication of individual component techniques. As part of our future effort to verify its effectiveness, the proposed method will be applied to railway structures that were severely damaged in the Hyogo-ken Nambu Earthquake and the Niigata-Chuetsu Earthquake to clarify the relationship between a structures’ anti-catastrophe resistance $R$ prior to the earthquakes evaluated with the method and the damage they actually sustained.

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