# Special edition paper

# Statistical Analysis of Relation between Earthquake Intensity and Damage Generation on Viaducts with and without Seismic Reinforcement

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East Japan Railway Company has reinforced viaducts based on experience derived from the 1995 Great Hanshin-Awaji Earthquake. If train operation control values for earthquakes can be raised corresponding to the improvement of the aseismic performance of viaducts, train operation could be more stable. We statistically analyzed the relation between earthquake intensity and damage generation on viaducts with and without reinforcement. We confirmed that there is some damage at viaducts whose columns were reinforced or judged to be unnecessary to reinforce; however, earthquake intensity estimated at those viaducts was larger than earthquake intensity that caused damage to viaducts without reinforcement.

●Keywords: Earthquake, Operation control, Seismic reinforcement, Viaduct, SI value

## 1 Introduction

East Japan Railway Company (JR East) has been performing seismic reinforcement of reinforced concrete (RC) viaduct columns and piers since the 1995 Great Hanshin-Awaji Earthquake as a structural countermeasure against earthquake damage. Seismic reinforcement in an order of tens of thousands of viaducts columns and piers has been completed for Shinkansen lines and conventional lines in the greater Tokyo area, with construction still in progress.[1] Seismic reinforcement methods differ depending on construction conditions[2], with seismic reinforcement by wrapping steel sheets shown in Fig. 1 being adopted for many sites.

As a non-structural countermeasure against earthquake damage, train operation control is implemented where train operation is suspended or speed restricted when seismic motion in excess of a certain level is observed. Spectrum intensity[3] (SI) is used as an index of seismic motion that has high correlation to damage.[4] Table 1 shows operation control classifications and operation control threshold values for conventional lines in earthquakes. Seismic design sections are those where structures were designed and constructed under the seismic design standard established by Japanese National Railways (JNR) in September 1979 in light of damage suffered in the 1978 Miyagi Offshore Earthquake, and structures there have high overall aseismic performance. Rockfall sections are mountainous sections with a risk of rockfall in earthquakes. Ordinary sections are those that do not fall under either rockfall sections or seismic design sections, and sections made up of viaducts designed and constructed before the aforementioned standard are classified as ordinary sections.

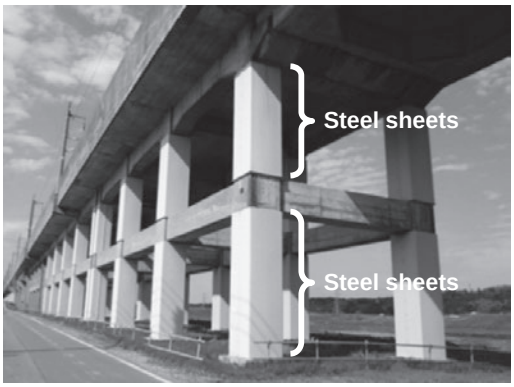


Fig. 1 Seismic Reinforcement by Wrapping Steel Sheets

Table 1 Operation Control Classifications and Operation Control Threshold Values for Conventional Lines in Earthquakes

| Operation control classification | Rockfall section | Ordinary section | Seismic design section |
|---|---|---|---|
| Speed restriction (kine) | 3 to less than 6 | 6 to less than 12 | 9 to less than 18 |
| Operation suspension | 6 or greater | 12 or greater | 18 or greater |

The objective of seismic reinforcement is to heighten aseismic performance of columns and piers and prevent the tremendous damage that would occur from slabs and bridge girders falling, thus improving safety of railways against earthquakes. Seismic reinforcement is performed for those objectives, but if aseismic performance is improved for viaducts overall, it may be possible to improve operation control threshold values in earthquakes.

While seismic design heightens aseismic performance of the viaduct as a whole, aseismic performance is only improved directly for columns and piers with seismic reinforcement. For that reason, in order to evaluate possibility of improving operation control threshold values, we need to analyze whether or not aseismic performance of the viaduct as a whole is raised by seismic reinforcement of columns and piers. As evaluation of aseismic performance, we both statistically analyzed the relation between viaduct damage generation and earthquake intensity and structurally analyzed using numerical models. In statistical analysis, we separated columns and piers into those with and without seismic reinforcement and analyzed the relation between earthquake intensity in past earthquakes and viaduct damage. Then we compared the relation between the ratio of the number of locations with damage out of the total number of viaducts (hereinafter, "damage occurrence rate") and earthquake intensity as well as the earthquake intensity at which damage starts to occur (hereinafter, "damage lower limit value"). Structural analysis is analytical evaluation of aseismic performance using numerical models of a viaduct. In this report, we cover the results of statistical analysis.

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Table 2 Earthquakes Studied

| Earthquake name | Moment magnitude | Date of occurrence |
|---|---|---|
| Mid Niigata Prefecture Chuetsu Earthquake | 6.6 | Oct. 23, 2004 |
| Chuetsu Offshore Earthquake | 6.6 | July 16, 2007 |
| Iwate–Miyagi Nairiku Earthquake | 6.8 | June 14, 2008 |
| Great East Japan Earthquake (mainshock) | 9.0 | March 11, 2011 |
| Great East Japan Earthquake (aftershock) | 7.1 | April 7, 2011 |

## 2 Statistical Analysis of the Relation between Earthquake Intensity and Viaduct Damage

In statistical analysis of the relation between earthquake intensity and viaduct damage, viaduct columns and piers were separated in to those with and those without seismic reinforcement and the relation between earthquake intensity and viaduct damage in past earthquakes analyzed to compare damage occurrence rate and damage lower limit value. In this study, we used the five earthquakes from the 2004 Mid Niigata Prefecture Chuetsu Earthquake shown in Table 2 in which damage to JR East railway facilities was suffered.

### *2.1 Data Sorting of Viaduct Seismic Reinforcement and Damage*

Structures analyzed were rigid frame and girder RC viaducts on JR East conventional and Shinkansen lines designed and constructed under standards in place before the aforementioned standards put together by JNR in 1979.

Fig. 2 shows the concept of viaduct classifications set to compare presence/absence of damage to viaducts and status of implementing seismic reinforcement on columns and piers. Rigid frame viaducts are composed of integral structures made up of columns, beams, and slabs (hereafter, "blocks") and adjustment girders, so we considered blocks and adjustment girders to each be a single classification in this research. For girder RC viaducts, we considered a span to be a single classification. At that time, we associated piers with beams on one side so the same damage would not be tabulated multiple times.

We organized presence/absence of damage to viaducts at individual earthquakes according to the classifications shown in Fig. 2. In evaluation of seismic capacity[5] previously done before seismic reinforcement, locations where a certain level of aseismic performance was confirmed and that seismic reinforcement was judged to not be needed were classified as "unnecessary to reinforce" and locations where it was judged that seismic reinforcement was needed because a certain level of aseismic performance was not met were classified as "necessary to reinforce". Of the places necessary to reinforce, those where seismic reinforcement was done on all columns and piers in a classification were deemed as "reinforced" and those where seismic reinforcement was not done on any of the columns and piers in a classification were deemed as "unreinforced". Locations where seismic reinforcement was done on some of the columns and piers in a classification and locations where it was unclear whether or not seismic reinforcement was done were omitted from statistical analysis.

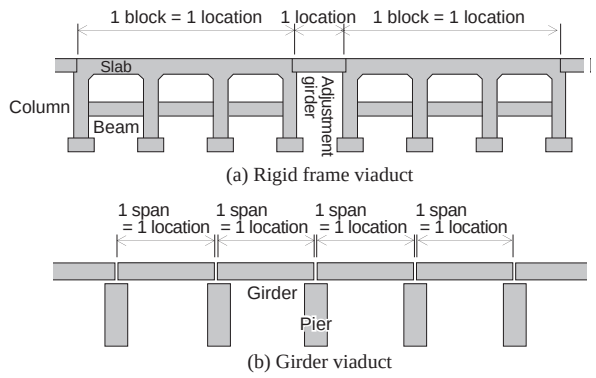



Fig. 2 Concept of Viaduct Classifications in Statistical Analysis

We investigated presence/absence of viaduct damage by individual viaduct classification shown in Fig. 2 based on materials such as disaster records. In the 2004 Mid Niigata Prefecture Chuetsu Earthquake and in the mainshock and the aftershock of the 2011 Great East Japan Earthquake, there were 163 locations of damage to viaducts where columns and piers were reinforced, unreinforced, or unnecessary to reinforce. Forms of damage to viaducts were slight damage involving cracking on columns and girders and damage such as flaking of concrete on columns and girders to expose rebar over a wide range. The latter affected the main functions of viaducts and obstructed train operation. In this research, we referred to items in materials such as disaster records related to scope of damage and presence/absence of obstructions to train operation and classified damage as that obstructing operation that not obstructing operation. Damage obstructing train operation occurred at 128 locations (78.5% of the damage) as shown in Fig. 3. In this research, the objective is to evaluate possibility of improving operation control threshold values, so we evaluated damage occurrence rate and damage lower limit for viaducts at the 128 locations with damage obstructing train operation in past earthquakes. Looking at damage obstructing train operation by individual structural type of member, we see as shown in Fig. 3 that there were many locations of column damage (53), followed by beam damage (30) and damage to concrete blocks (side blocks) for preventing beam displacement (26).

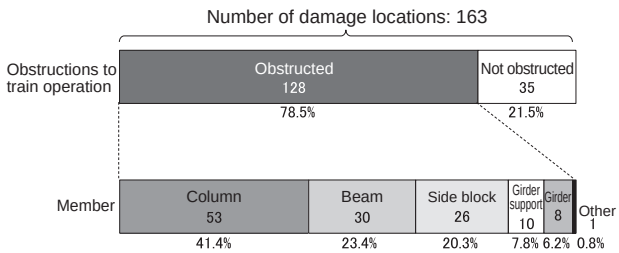



Fig. 3 Number of Locations with Damage on Viaducts where Columns are Unreinforced, Reinforced, and Unnecessary to Reinforce

### *2.2 Comparison of Seismic Intensity Estimation and Viaduct Damage*

In order to analyze the relation between seismic intensity and viaduct damage, seismic intensity along railway lines needs to be evaluated. However, the interval between seismometers along the railway is in the order of tens of kilometers, so seismic intensity at locations without seismometers needs to be estimated. We therefore estimated seismic intensity using a method of estimating spatial distributions of ground motions[6].

Fig. 4 shows an image of estimating spatial distributions of seismic intensity. First, we calculated seismic intensity at the engineering bedrock by dividing seismic intensity observed in the individual earthquakes by site amplification. Then, we spatially interpolated seismic intensity at the engineering bedrock to find the spatial distribution. Spatial interpolation was performed by the Simple Kriging method[7], which can take into account the tendency of seismic motion to attenuate according to the distance from the hypocenter. Finally, we multiplied the area-wide distribution of seismic intensity at the engineering bedrock by site amplification to estimate spatial distribution of seismic intensity at the ground surface.

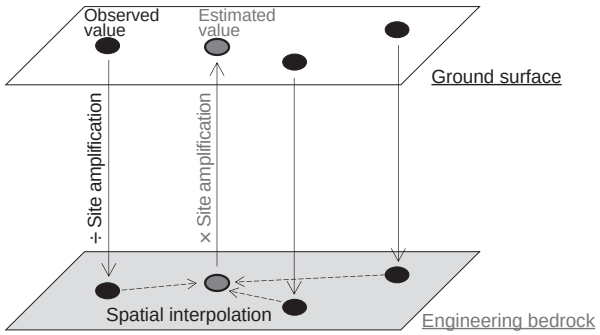



Fig. 4 Image of Estimating Spatial Distribution of Seismic Intensity

For seismic intensity, we used SI values that JR East uses in train operation control. For values observed by seismometers, we used those of the K-NET and KiK-net strong-motion seismograph networks of the National Research Institute for Earth Science and Disaster Resilience (NIED) and those for train operation control used by JR East. For site amplification, we used site amplification factors[9] of the subsurface ground per 250 m mesh for all of Japan estimated from geomorphologic classification[8].

We compared estimated seismic intensity and viaduct damage by classifications shown in Fig. 2. In viaducts in classifications with estimated seismic intensity in SI values of less than 10 kine, not even slight damage occurred, so they were omitted from those for statistical analysis. Fig. 5 shows the number of statistically analyzed locations and number of locations with damage. Of the 23,847 locations statistically analyzed, a total of 17,844 of those locations were classified as viaducts necessary to reinforce and 6,003 were classified as unnecessary to reinforce. And of the viaducts necessary to reinforce, 13,385 were unreinforced and 4,469 were reinforced. The number locations of damage was 81 on unreinforced viaducts, seven on reinforced viaducts, and 40 on viaducts unnecessary to reinforce, meaning damage occurred on less than 1% of statistically analyzed locations.

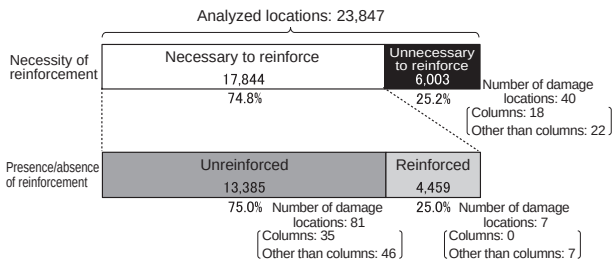



Fig. 5 Number of Statistically Analyzed Locations and Number of Locations with Damage

## 3 Results of Statistical Analysis

We compared damage occurrence rate and damage lower limit value per viaduct where columns and piers were unreinforced, reinforced, and unnecessary to reinforce. Damage occurrence rate was defined by the following equation.

$$\text{Damage occurrence rate (\%)} = \frac{\text{Cumulative number of damage locations for up to a certain SI value}}{\text{Cumulative number of locations with up to a certain SI value}} \times 100 \quad (1)$$

Fig. 6 shows the relation between damage occurrence rate and SI value for all viaduct members. Damage occurrence rate tends to become higher the larger the SI value. Damage occurrence rate is lowest for reinforced viaducts, and it becomes larger for viaducts unnecessary to reinforce and unreinforced viaducts in that order. Damage lower limit value is 26.7 kine for unreinforced viaducts, 36.6 kine for reinforced viaducts, and 28.8 kine for unnecessary to reinforce viaducts, and damage lower limit for viaducts unnecessary to reinforce and reinforced viaducts was higher than that for unreinforced viaducts. Moreover, the damage lower limits above were higher than the 21.8 kine[4] damage lower limit of major structures (bridges, viaducts, embankments, excavations, natural slopes, and retaining walls) investigated when setting current operation threshold values of ordinary sections shown in Table 1. From this, aseismic performance of the viaduct as a whole may possibly be increased by seismic reinforcement of columns and piers. Note that in Fig. 6, there is a range where damage occurrence rate is reduced. This is because if damage does not occur in a certain SI value range, just the accumulation of number of locations corresponding to the denominator of Equation (1) increases.

Next, we separated damage to columns and piers and that to other members and investigated damage occurrence rate and damage lower limit. Fig. 7 (a) shows the relation between damage occurrence rate for columns and piers and SI value. There was no clear difference in both damage occurrence rate and damage lower limit of columns and piers for unreinforced viaducts and viaducts unnecessary to reinforce. Columns and piers of reinforced viaducts were not damaged in the earthquakes studied this time, so damage occurrence rate for those was 0%. This is assumed to be because aseismic performance of columns and piers was improved due to seismic reinforcement. Next, Fig. 7 (b) shows the relation between damage occurrence rate for members other than columns and piers and SI value. Damage

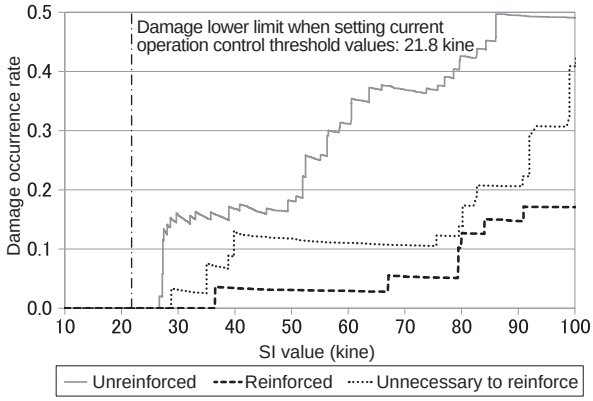
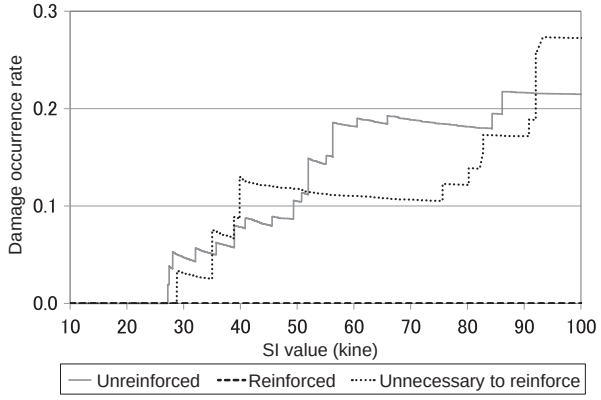
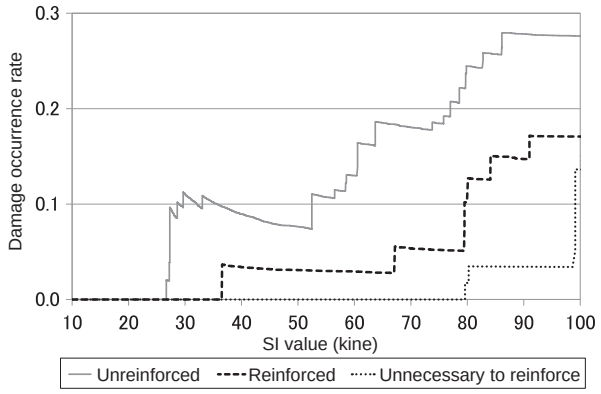



Fig. 6 Relation between SI Value and Damage Occurrence Rate (all viaduct members)




(a) Columns and piers




(b) Other than columns and piers

Fig. 7 Relation between SI Value and Damage Occurrence Rate (by member)

occurrence rate was highest for unreinforced viaducts, and it becomes lower for reinforced viaducts and viaducts unnecessary to reinforce in that order. Damage lower limit was 26.7 kine (side block damage) for unreinforced viaducts, 36.6 kine (beam damage) for reinforced viaducts, and 79.6 kine (beam damage) for viaducts unnecessary to reinforce. From this, we find that compared to unreinforced viaducts, damage occurs less on members other than columns and piers on reinforced viaducts and viaducts unnecessary to reinforce. However, in statistical analysis by type of member, the number of locations of damage was small as shown in Fig. 5, so damage occurrence rate and damage lower limit may be affected by that.

## 4 Conclusion

For viaduct sections where seismic reinforcement has been completed, we separated columns and piers into those with and without seismic reinforcement and conducted statistical analysis on the relation between earthquake intensity and viaduct damage in order to evaluate the possibility of improving train operation control threshold values of ordinary sections. As a result of analyzing five past earthquakes where JR East railway facilities suffered damage, we came to the following findings.

- Damage occurrence rate of all viaduct members was lowest for seismic reinforced viaducts, becoming larger for viaducts unnecessary to reinforce and unreinforced viaducts in that order.
- Damage lower limit value of all viaduct members was 26.7 kine for unreinforced viaducts, 36.6 kine for reinforced viaducts, and 28.8 kine for viaducts unnecessary to reinforce, and damage lower limit for reinforced viaducts and viaducts unnecessary to reinforce was higher than that for unreinforced viaducts. Those were higher than the 21.8 kine when setting current operation control threshold values.

The findings showed that, in terms of statistical analysis of the relation between seismic intensity and viaduct damage, overall viaduct aseismic performance is increased by seismic reinforcement of columns and piers. However, statistical analysis by type of member may be affected by the small number of locations of damage, so future studies will be necessary. Also, there were many instances of operation being obstructed by power poles tilting and breaking in the 2011 Great East Japan Earthquake[10], so we intend to conduct statistical analysis on the relation between seismic intensity and damage to power poles and tracks in viaduct sections. Moreover, we intend to evaluate aseismic performance from a perspective of structural analysis using numerical models of viaducts and comprehensively evaluate the possibility of improving operation control threshold values from the perspectives of both statistical analysis and structural analysis.

Acknowledgements
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