Characteristics of Uplift Force Acting on Bridge Bearings during Earthquakes

Masamichi SAITO
Steel & Hybrid Structures Laboratory, Structures Technology Division

Tatsuya NIHEI
Concrete Structures Laboratory, Structures Technology Division

Yugo DOUCHI
Concrete Structures Laboratory, Structures Technology Division

This study aims to reveal the characteristics of and factors influencing uplift forces acting on bridge bearings during earthquakes. Firstly, three different analysis models were compared through seismic response analyses in order to select a suitable model for parametric analysis. Secondly, factors influencing the uplift force were investigated by examining the seismic response analyses of six different bridge models of normal Japanese steel railway bridges. Finally, a nonlinear hysteresis model of a bridge bearing was proposed and the influence of using this model was investigated. As a result, it was confirmed that the response displacement does not exceed the limit displacement even during large-scale earthquakes.

**Keywords:** bridge bearing, uplift force, vertical ground motion, horizontal ground motion

1. Introduction

In the seismic design of Japanese steel railway bridge bearings, structural members to resist uplift force are installed such as anchor bolts and pinch plates, etc. The dimensions of these structural members are determined in a way that ensures they will have the capacity to resist uplift forces acting vertically upwards on the bearing section. Uplift forces are generated from girder vibrations caused by vertical ground motion and overturning moments produced by horizontal ground motion, as shown in Fig. 1.

In conventional designs, the uplift force generated by vertical ground motion is defined as half the horizontal seismic inertial force, without considering the behavior of the girders and bearing sections. This method can lead to overestimation of the uplift force and lead to an increase in the size of members designed to resist uplift force, and the size of the bearing body. Uplift force produced by horizontal ground motion is calculated using horizontal force in transverse direction and the ratio of the height of girder centroid H to the interval between bearings W (H/W).

The verification of bearings for these uplift forces is carried out separately for vertical and horizontal ground motions, although the responses to each ground motion can occur concurrently.

Based on these premises, this study aims to reveal the characteristics and factors that influence uplift forces acting on bridge bearings during earthquakes. Firstly, the authors selected an analysis model type by comparing the response of three different models in seismic response analyses. Secondly, the characteristics and factors influencing uplift forces were investigated through seismic response analyses of six different model bridges and changing their dimensions as parameters. Finally, a nonlinear hysteresis model of bearing is proposed and is investigated on the influence of the nonlinearity to the response.

2. Selection of modelling method

2.1 Outline and analysis method

To carry out the parametric analysis shown in the next chapter, analysis models need to be able to reproduce the vertical force on bearings and their variables need to be easy to change. In this chapter, seismic response analyses were carried out with three different analysis models to determine the appropriate modelling method.

The target bridge was a simple spanning composite girder with double track and an 80 m span. Three analysis models were built applying different modelling methods: Type 1 was a "detailed model" with shell and solid elements and made for the purpose of comparison with other models. In the Type 2 model, the girders were modelled as beam elements. In the Type 3 model, the girders were modelled as particle elements. The bearings and piers were modelled in the same way in all three models.
2.2 Results

Figure 2 shows the time history of the vertical force acting on the bearings. Negative vertical force values represent compressive force while positive values represent tensile force, i.e. uplift force.

The Type 2 model with beam elements was able to reproduce the maximum value of the vertical force in the detailed Type 1 model. On the other hand, the results from the Type 3 model with particle elements were different to those from the Type 1 model. These results demonstrate that it is important for the analysis model to include the effect of girder vibration in order to obtain accurate vertical forces on the bridge bearings. The authors selected the Type 2 model for the parametric study in the next chapter.

![Comparison of analysis model (Kobe EQ, 1995)](image)

3. Investigation of influential factors on uplift force

3.1 Outline

In order to clarify the characteristics and factors influencing uplift force, a parametric study using seismic response analyses was carried out.

3.1.1 Analysis model

Table 1 shows the properties of the model bridges. From normal Japanese railway bridges, six bridges with a different span, girder height and bearing interval were modelled. The analysis models were built on the basis of the Type 2 model selected in the previous section, using beam elements.

Table 2 shows the properties of the bridge piers. In the horizontal direction, the piers are modelled as fixed condition, linear elastic and nonlinear plastic state. For the non-
linear plastic state (Cases 3 and 4), Clough’s model was applied for the hysteresis model. In the vertical direction, the piers were modelled as fixed condition. In all cases, bearings were modelled as fixed condition.

The damping coefficient of the models was set as 1%, considering that the normal damping coefficient of steel railway bridges is around 1-2%.

### 3.1.2 Ground motion

Figure 3 shows the acceleration response spectra of the earthquake ground motions applied in the analyses. Five different earthquake ground motions were applied.

Figure 3 (a) and (b) are design earthquake motions from the design standard [1], given for each ground condition (G0-5). The current version of the seismic design code stipulates that half the horizontal response spectrum on a bedrock surface (G0 ground) can be applied for vertical ground motion, as shown in the graphs in the figures. Other ground motions shown in Fig.3 (c) – (d) are observed actual earthquakes.

Each case analysis is carried out for the three different ground motion input methods: only vertical direction input (V), only horizontal direction input (H) and concurrent input of both directions (VH).

### 3.2 Results

#### 3.2.1 Uplift force by vertical ground motion

Figure 4 shows the vertical force \( P_v \), from the result of Case IV (Fixed piers, only vertical GM). The figures also show the acceleration response spectra of the input ground motions. The vertical force is equal or less than the force calculated from the spectra. These facts indicate that the vertical force generated by vertical ground motion is mainly affected by the natural period of girder in the vertical direction and is predictable using the spectra.

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**Table 1** Properties of model bridges

| Bridge | Type            | Span (m) | No. of Track | Track type       | Footway (weight) | Natural period (s) | H/W*2 |
|--------|-----------------|----------|--------------|------------------|------------------|-------------------|-------|
| 1      | Composite girder| 30.8     | Single       | Ballasted track  | -                | 0.22              | 1.03  |
| 2a     | Deck girder     | 47.5     | Single       | Direct fasten    | -                | 0.22              | 0.15  |
| 2b     | Deck girder     | 47.5     | Single       | Direct fasten    | 5%               | 0.23              | 0.15  |
| 2c     | Deck girder     | 47.5     | Single       | Direct fasten    | 10%              | 0.23              | 0.15  |
| 3a     | Composite girder| 43.5     | Single       | Slab track       | -                | 0.45              | 1.31  |
| 3b     | Composite girder| 43.5     | Double       | Slab track       | -                | 0.45              | 0.43  |
| 4      | Composite girder| 68.0     | Double       | Slab track       | -                | 0.51              | 0.69  |
| 5      | SRC girder      | 17.4     | Single       | Slab track       | -                | 0.22              | 0.29  |
| 6      | Composite girder| 80.0     | Double       | Slab track       | -                | 0.53              | 0.57  |

*1: Weight ratio (Footway / Girder)  
*2: Shape ratio of girder (Centroid height / Bearing interval)

**Table 2** Properties of model piers

| Case | Pier (Horizontal direction) | Natural period of pier (s) | Yielding point of pier (Seismic coefficient) | Focus point |
|------|-----------------------------|----------------------------|---------------------------------------------|-------------|
| Case 1 | Fixed                      | Fixed                      | Fixed                                       | Behavior of girder |
| Case 2 | Linear elastic             | 0.45                       | No yielding point                           | Influence of pier rigidity |
| Case 3 | Nonlinear Clough's model   | 0.45                       | 0.5                                        | Influence of pier yielding |
| Case 4 | Nonlinear Clough's model   | 0.45 (Pier 1)              | 0.5                                        | Influence of difference in displacement |

**Fig. 3** Acceleration response spectrum of vertical and horizontal ground motions

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3.2.2 Uplift force by horizontal ground motion

Figure 5 shows the maximum horizontal force $P_h$ acting on the bearings from the results of Case 1H-4H (Horizontal GM). The time period on the graphs are the natural periods calculated from the first order mode through an eigenvalue analysis of the whole bridge system.

Most of the cases, horizontal forces are equal or less than the force calculated from the acceleration response spectra. Comparing the differences in each case, Case 2 (linear piers) shows the largest horizontal forces because the bridge systems’ natural periods are corresponding to the maximum values of the response spectrum. When the piers have nonlinearity (Case 3), the horizontal forces become smaller. Even when the piers had different natural periods (Case 4), the horizontal forces were smaller than the case of linear piers (Case 2).

Figure 6 shows the relationship between the ratio of vertical force to horizontal force ($P_v / P_h$) and the ratio of girder centroid height to the bearing interval (H/W). In the models without eccentricity, the relationship was linear. In the models with eccentricity caused by footways aside the girders, the vertical forces are larger than those of the models without eccentricity. These facts indicate that the vertical force in the horizontal ground motion is mainly affected by the horizontal force $P_h$, the ratio H/W, and the eccentricity of the girder centroid.

3.2.3 Influence of concurrency of vertical and horizontal ground motions

Figure 7 shows the analysis results with concurrent vertical and horizontal ground motions (Case 1VH and Case 3VH) in the relationship with analysis results from a single ground motion. It is found that the vertical force on bearings with concurrent ground motions become larger than that with single ground motion. However, in the most cases the resultant vertical forces are less than 1.2 times of single ground motion and in some cases less than 1.4 times.
4. Evaluation of bearings with nonlinear model

4.1 Nonlinearity of bearings

In the cases with fixed bearing model, sometimes large forces are generated, as shown in the previous chapter. On the other hand, in actual earthquakes, the uplift resisting members (anchor bolts, etc.) tend to be damaged but do not reach fracture point in most cases. The authors consider that the nonlinearity of bearings is the cause.

In this chapter, seismic response analyses with nonlinear bearing models were carried out for the model bridge 1, shown in the previous chapter.

Figure 8 shows the hysteresis curve of the line bearing in the vertical direction. The line bearing manifests the points where there is a change in stiffness by the debonding of anchor bolts or yielding of pinch plates [2]. In this study, the authors propose a hysteresis model considering the debonding of an anchor bolt.

4.2 Influence of nonlinearity of bearings

Figure 9 shows the analysis results of models with fixed bearings and those with nonlinear bearings. With nonlinear bearings, upward displacement increases despite increasing uplift force in the models with fixed bearings. In this case, the maximum displacement does not exceed the limit displacement, which is defined as the lap of the sole plate and the side block. Comparing Case 1VH with Case 1VH, maximum displacements are almost equal although these two cases in the condition of fixed bearings show different uplift forces. It indicates that there is a possibility that the concurrency of vertical and horizontal ground motions has less influence than the fixed bearing condition.

5. Conclusions

In this study, the authors investigated the characteristics and factors influencing the uplift force acting on bearings during earthquakes through seismic response analyses.

The main sources of the uplift force on bearings are as follows:
- Vertical ground motion: natural period of girder.
- Horizontal ground motion: horizontal force $P_h$, the ratio $H/W$, and eccentricity of the centroid.

Even in large-scale earthquakes, evaluation using a nonlinear hysteretic model shows that the response upward displacement does not exceed limits, and that the effect of
concurrency of vertical and horizontal ground motions does not affect the response displacement of the bearings.

When the natural period of a bridge exceeds 0.5s and its H/W is small, no uplift force acts on its bearings during an earthquake. These findings could make it possible to reduce the size of bridge bearings and cut the cost of their manufacture.

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Authors

Masamichi SAITO, Dr. Eng.
Assistant Senior Researcher, Steel & Hybrid Structures Laboratory, Structures Technology Division
Research Areas: Steel Structures and Hybrid Structures

Yugo DOUCHI
Researcher, Concrete Structures Laboratory, Structures Technology Division
Research Area: Concrete Structures

Tatsuya NIHEI, Dr. Eng.
Senior Researcher, Steel & Hybrid Structures Laboratory, Structures Technology Division
Research Areas: Concrete Structures and Hybrid Structures