# SEISMIC RETROFIT OF EXISTING HIGHWAY BRIDGES CONSIDERING DISPLACEMENT RESTRAINT EFFECT OF ABUTMENTS

Shigeki UNJOH1), Hiroshi KOBAYASHI2) and Yusuke OGURA3)

## ABSTRACT

To develop the seismic performance evaluation methods and seismic retrofit methods for existing highway bridges considering a whole bridge system including abutments and backfill soils, the earthquake response behavior is studied through parametric analyses. From the study, it is found that the restraint effect of abutment on the longitudinal displacement response of girder and columns is significant and that the effect should be appropriately considered in the evaluation of seismic performance of existing bridges.

## 1. INTRODUCTION

After the 1995 Kobe Earthquake, the seismic retrofit program for existing highway bridges on land area have been progressed steadily by using conventional retrofit measures including concrete and steel jacketing methods. However, there have been many cases in which the usual jacketing retrofit measures for reinforced concrete columns have the cost and construction restriction condition problems particularly as for river bridges. Since the retrofit of columns of the river bridges generally needs a temporary cofferdam for the jacketing works, the cost and environmental effect on the river water becomes significant. Therefore, the effective and economical retrofit methods for such bridges have been to be developed.

On the other hand, the river bridges generally have abutments at both ends of girder in/on the river embankment. The expansion gap between abutments and the end of girders are generally small about less than 10 cm for usual existing bridges. Therefore, when a large earthquake occurs, the contact or collision between the girder and abutments happens and then the longitudinal displacement of the girder is expected to be restrained by the effect of abutments. As a results of the restriction of the longitudinal displacement response of girders, the inertia force from the girder to the columns is also expected to be decreased, then eventually the damage to the columns is to be limited. Therefore, it is important to appropriately consider the restraint effect of abutments to rationally evaluate the seismic performance of existing river bridges.

Investigating the past earthquake damage experiences to the bridge structures, several examples, in which although the girder and abutment were collided each other and the damage at the end of girder and abutment was developed, the damage to main members including columns was not significant, have been found. This kind of restraint effect has not yet considered in the current seismic design even for new bridges because

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of the difficulty and uncertainty of the performance evaluation of the behavior of abutment and backfill soils. Since the abutments generally consists of foundation, wall, parapet, wing walls at left and right hand sides, and backfill soils. Therefore, the abutments have relatively large reaction characteristics in the backward direction of abutments.

The objectives of this research is to develop the seismic performance evaluation methods and seismic retrofit methods considering a whole bridge system behavior including the displacement restraint effect of abutments. This paper presents the analytical study on the displacement restraint effect of abutments on the whole bridge behavior.

## 2. ANALYSES OF A WHOLE BRIDGE SYSTEM CONSIDERING THE COLLISION EFFECT

### 2.1 Analytical Model of A Whole Bridge System

**Fig.1** shows the nonlinear analytical model of a whole bridge system to study the effect of collision effect between girder and abutments. **Fig.2** shows more detailed model of abutment and columns. The bridge analysed in this study is 5-span continuous steel girder bridge with bridge length of 200m. The girder is assumed to be supported by rubber bearings and/or fixed/movable bearings at columns and abutments. The both ends of girder are supported by the abutments with height of 10m. The columns are 10m high and the ground condition is assumed to be Type II (medium stiff) ground. The columns are modeled as a nonlinear beam model with Takeda type hysteresis characteristics and the spring model with nonlinear moment-rotation hysteresis relation is placed at the bottom of columns. The parapet is a reinforced concrete member then is modeled as nonlinear with Takeda Type hysteresis characteristics.

The backfill soils at the abutments are assumed to be sandy soil with N-value of 5 (shear resistance angle: 30 degree, unit weight: 19 $kN/m^3$) and are modeled as discrete nonlinear springs. The force-displacement relation of the backfill soil spring is zero in the direction of separation between abutment and backfill soil, and bilinear model in the direction of pushing side are assumed. **Fig.3** shows the nonlinear collision spring model and the spring coefficient is assumed to be $3 \times 10^6$ kN/m which is based on Kawashima's study [4].

The foundation of columns and abutments are modeled as linear spring with sway and rotation components. This is because the foundations of this bridge model is assumed to have enough strength than that of the columns. The contact/collision between girder and abutments is assumed to be made at the point located at 20 cm downward from the top of parapet.

### 2.2 Analytical Conditions

Three cases are assumed as the model of parapet: 1) No contact/collision (enough expansion gap between girder and abutment), 2) Usual design strength of parapet (contact/collision between girder and abutment. Nonlinear behavior of parapet is assumed.), and 3) Strengthened parapet (contact/collision between girder and abutment. Elastic behavior of parapet is assumed.).

The acceleration time history data recorded at the JR west Takatori station (Type 2 ground) was used as an input ground motion to the model bridge. The integration time of dynamic equations is assumed to be small enough as 0.0005 second to consider the collision effect. Rayleigh type damping is assumed to make damping matrix.

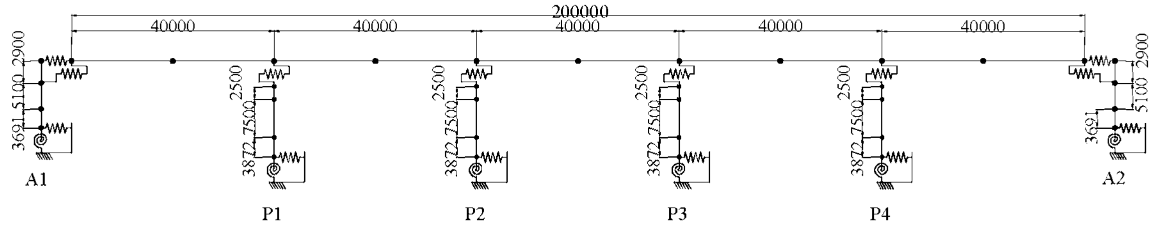


Fig.1 Whole Bridge Model

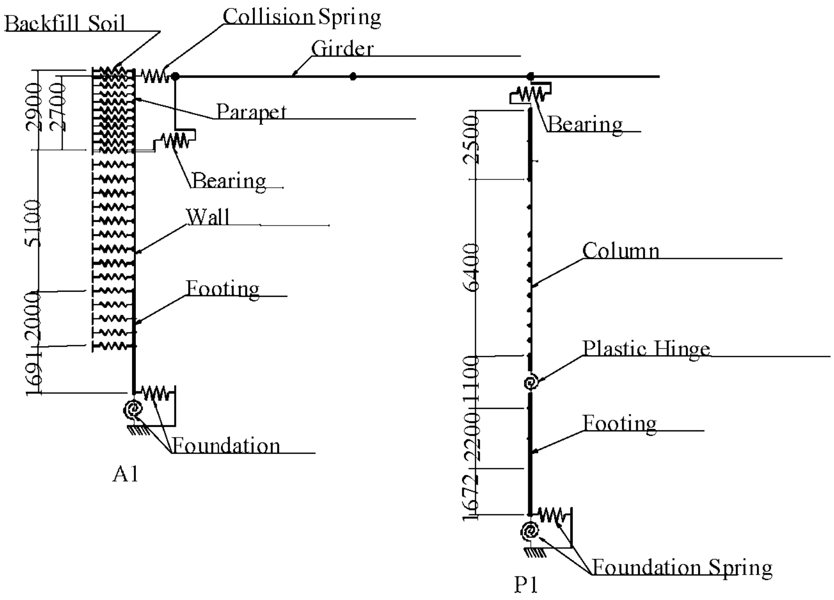


Fig.2 Detailed Model of Abutment and Columns

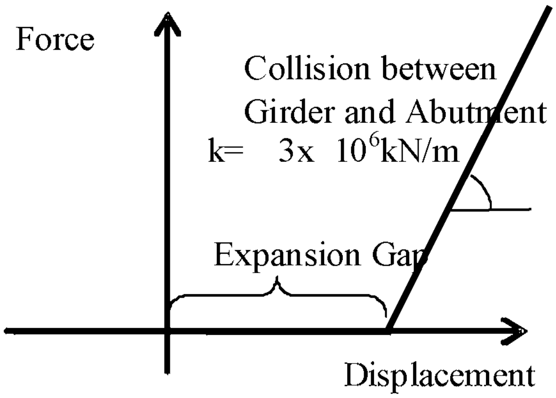
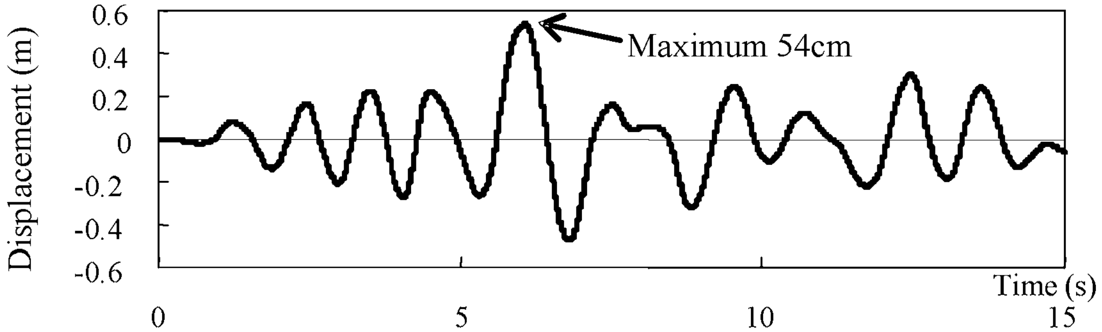


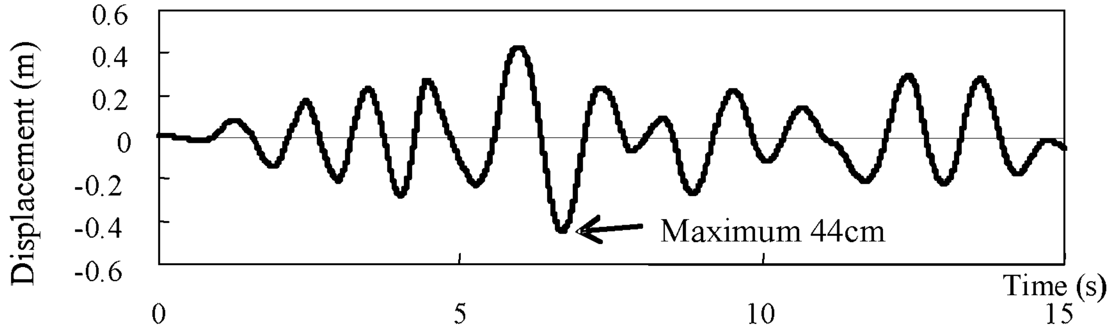
Fig.3 Collision Spring Model

### 2.3 Analytical Results

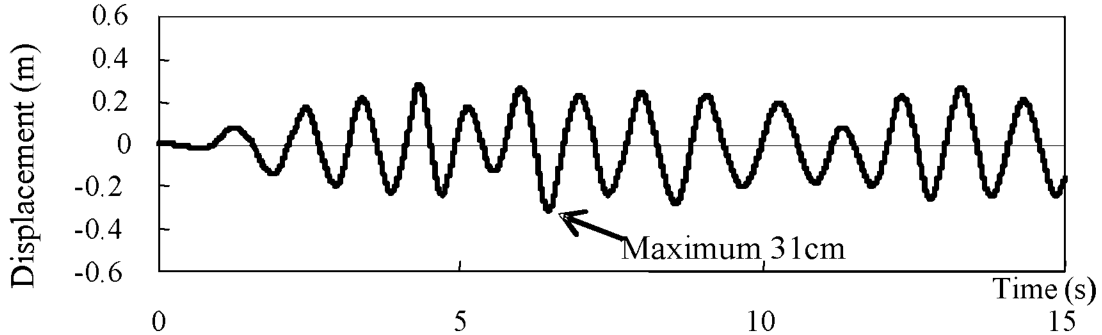
**Fig.4** shows analytical results on the response displacement of girder for three cases. The maximum displacement is significantly decreased by considering the restraint effect of abutment. For case 1) without any restraint, the maximum displacement is 54 cm, for case 2) with usual design parapet, it is decreased to 44 cm, and for case 3) with strengthened parapet, it becomes 31 cm. The maximum displacement is significantly decreased by the restraint effect of abutments. In case 2), the parapet behaved in nonlinear range and the maximum displacement response is 29 cm, which exceeds the ultimate limit of parapet. In case 3), the displacement of abutment is 12 cm, which is almost the same displacement of yield displacement of abutment obtained from the pushover analysis of the abutment.



(a) No Contact/Collision (Enough Expansion Gap)



(b) Usual Design Strength of Parapet

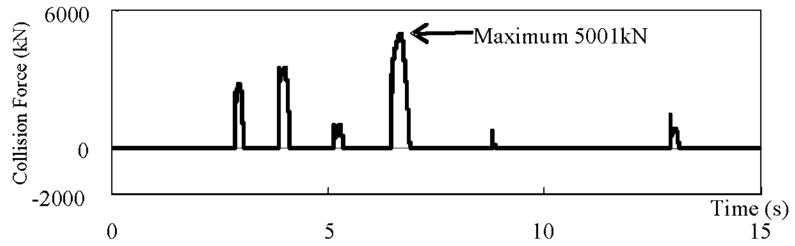


(c) Strengthened Parapet

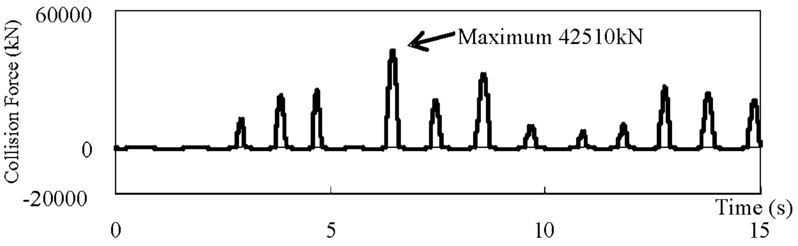
Fig.4 Time History Responses of Girder

**Fig.5** shows the time history data of reaction force developed at the collision spring. The number of collisions for case 3) is more than those for case 2). Maximum collision force was 5,000 kN for case 2) and 42,510 kN for case 3). To provide enough shear strength at the parapet against the collision forces, the necessary strength is satisfied by increasing the shear re-bars in the parapet.

Therefore, for this bridge analysed with the size around 5-span continuous bridges, considering the restraint effect of abutment, the maximum displacement response of girder is effectively decreased by the contact/collision between girder and abutments, then the displacement of columns is also decreased.



(a) Usual Design Strength of Parapet



(b) Strengthened Parapet

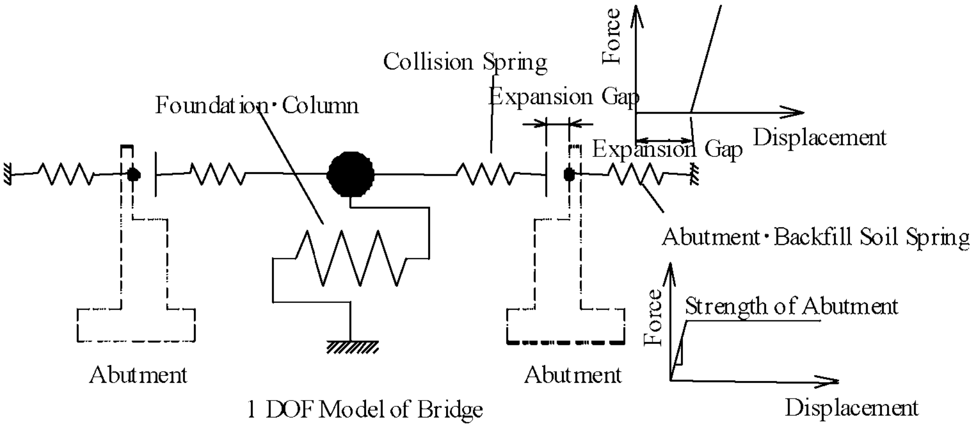
**Fig.5** Reaction Developed at Collision Spring at Abutment A1

## 3. PARAMETRIC ANALYSES ON THE COLLISION EFFECT

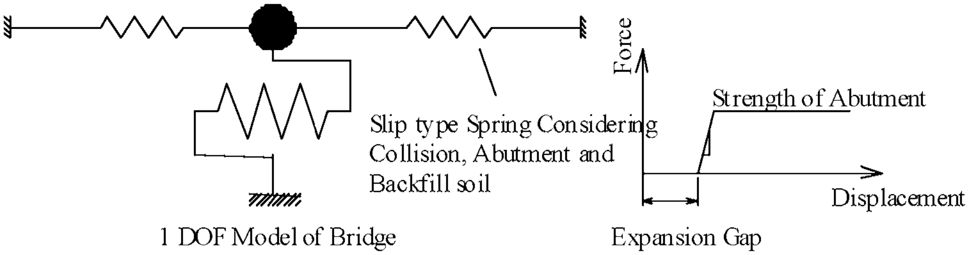
### 3.1 Simplified Analytical Model

The bridge analysed is assumed as 5-span continuous steel girder bridge as shown in **Fig.1**. The bearing support condition is modified as one fixed condition at P2 piers, the movable bearing condition is assumed on other piers and abutments. P2 column is redesigned as a fixed pier which supports 5-spans and has the yield strength with equivalent seismic coefficient of 0.265.

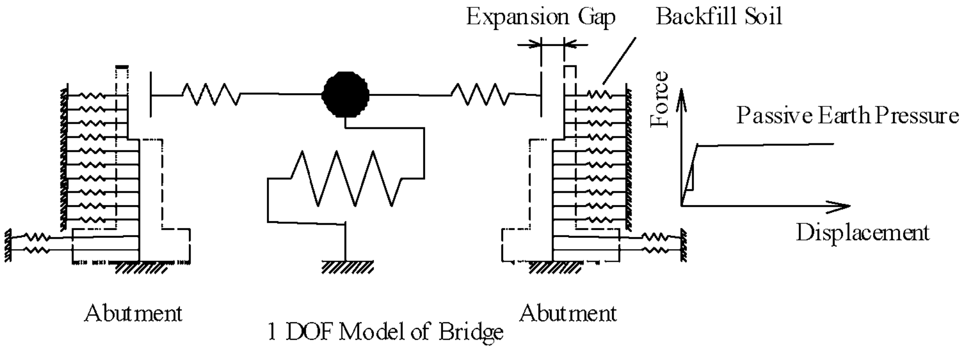
Three simplified models are proposed as shown in **Fig.6**. The whole bridge system consists of single-degree-of-freedom model and two nonlinear abutment models. The force-displacement relation of abutment and backfill soils are modeled as nonlinear spring characteristics obtained through static push-over analysis of abutments. The foundation is assumed as fixed for the simplicity. In three models, the model of abutment and backfill soils is changed; model 1) consists of collision spring and abutment spring model, model 2) consists of a simple spring model with nonlinear characteristics considering the expansion gap and reaction from abutment, model 3) consists of detailed model of abutment and backfill soils.



(a) Model 1



(b) Model 2



(c) Model 3

**Fig.6** Simplified Model

### 3.2 Analytical Cases

Analytical parameters are assumed as bridge length, strength of abutment parapet and backfill soils, expansion gap between girder and abutment, natural period of bridges. The bridge length is assumed as 5-span continuous bridges as shown in **Fig.1** as well as 2-span and 3-span in which the fixed condition column design was modified according to the inertia force from girder.

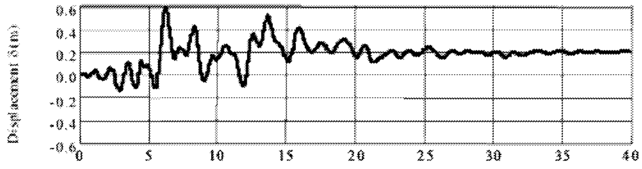
The force-displacement relation of parapet is modeled as three cases: case 1) reaction considering parapet and backfill soil (yield reaction force: 3,800 kN), case 2) reaction considering parapet, wings and backfill soils (yield reaction force: 11,000 kN), case 3) strong parapet (elastic behavior). The force-displacement relations for three cases are obtained through pushover analyses using model 3).

The expansion gap between girder and abutments is assumed as 6 cm (fundamental case) which was obtained from the usual design method considering the temperature change. And the expansion gap is assumed as 50%, 150%, and 200% as well as no limitation to study the effect of gap. The natural period of bridge is assumed as 0.8 second for the fundamental case and the natural period is changed as 70%(0.56 second) and 150% (1.2 second) in the analyses.

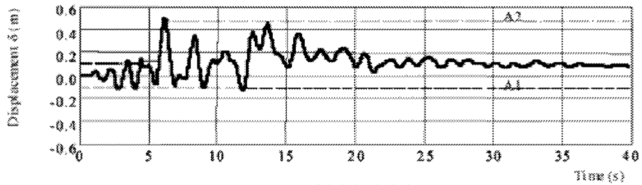
Eighteen design standard earthquake acceleration data for Level 2 earthquake are used as an input earthquake ground motion to the model.

### 3.3 Comparison of Simplified Models

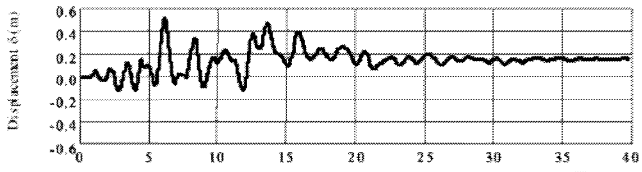
**Figs.7 and 8** show the comparison of the response displacement and reaction of abutment spring model between three models of abutments for a case of 5-span continuous girder bridges. The almost the same results are obtained. For model 3), the spike like response is found in the reaction of abutment spring. It is estimated as the



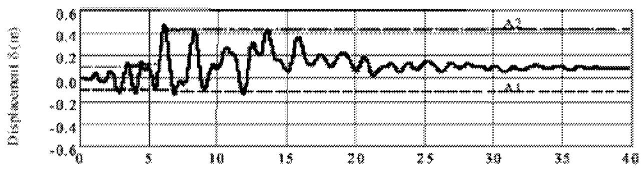
(a) No Contact/Collision (Enough Expansion Gap)



(b) Model 1

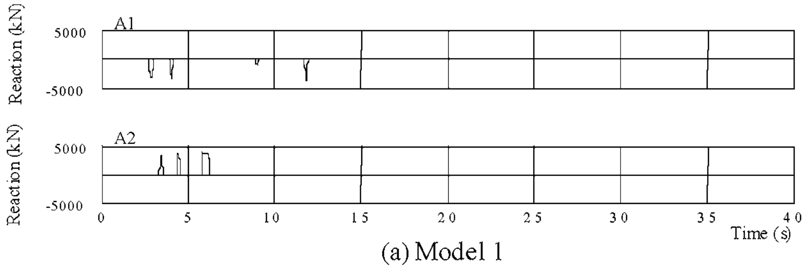


(c) Model 2

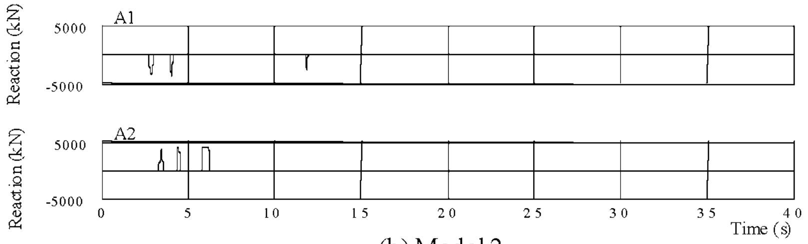


(d) Model 3

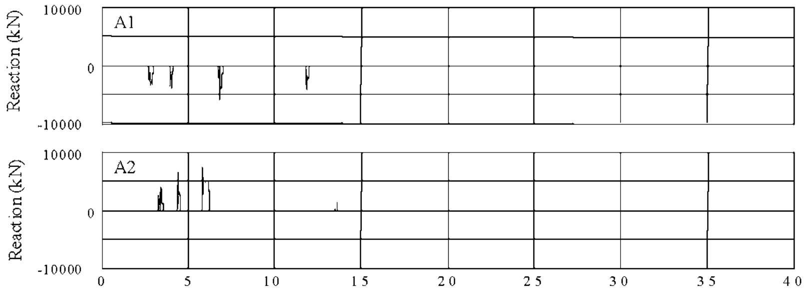
Fig.7 Comparison of Response Displacement between Three Simplified Models



(a) Model 1



(b) Model 2



(c) Model 3

**Fig.8** Comparison of Reaction Developed at Collision Spring

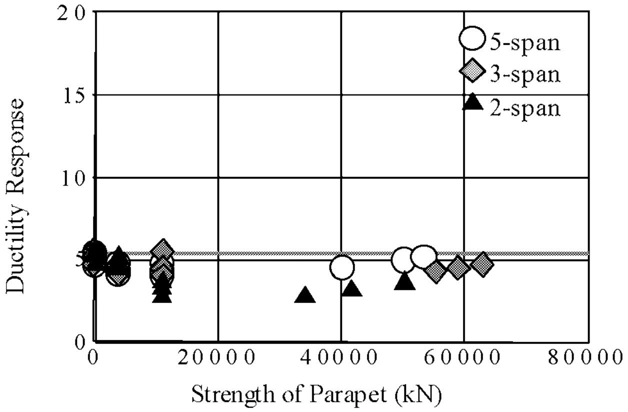
effect of inertia force of mass of abutment. Based on these results, the abutment can be modeled as simplest model of case 2). Therefore, in the following parametric analyses, model 2) is used.

### 3.4 Effect of Strength and Stiffness of Abutment

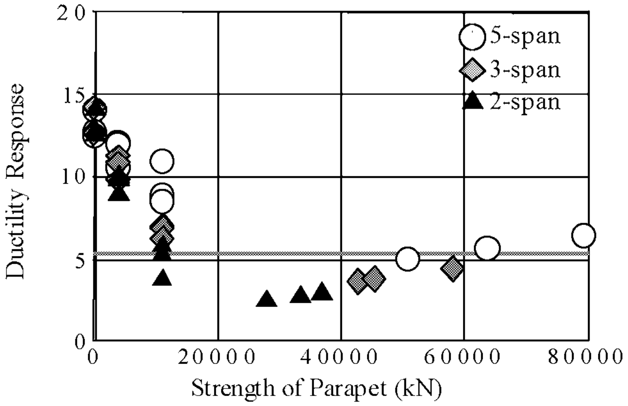
To study the effect of strength and stiffness of parapet to restrain the longitudinal displacement of girder, 3 cases of abutment condition were analysed as well as no collision case.

**Fig.9** shows the relation between the strength of abutment and ductility response of fixed column. The ductility response decreases with the increase of the strength of abutment. It means that by strengthening parapet and/or abutment the displacement of girder and the ductility response of columns can be effectively decreased during large earthquakes. Form a design point of view, the response displacement of fixed columns is less than the ductility capacity, the seismic retrofit works for the columns are not necessary.

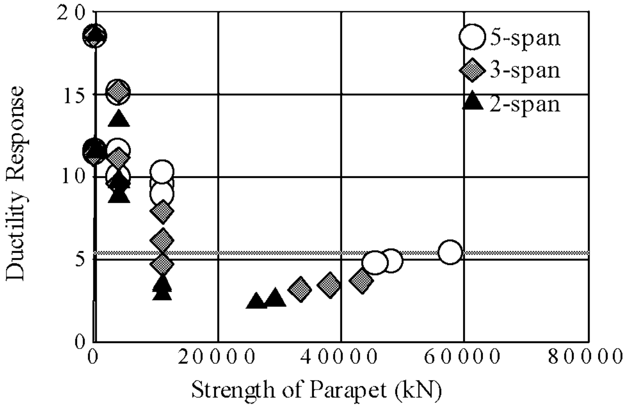
For cases of small bridges around two-span continuous girder bridges, the seismic performance was satisfied considering the restraint effect of parapet and wings. The same tendency is found in the past actual damage of two or three spans bridges. On the other hand, for multi-span bridges the careful consideration is needed not only the strengthening of the parapet and abutment, but other measures.



(a) Ground Type 1



(b) Ground Type 2



(c) Ground Type 3

**Fig.9** Relation between Strength of Parapet and Ductility Responses of Columns

The necessary level of strengthening of parapet and abutment, in which the columns ductility response is satisfied, is studied. **Table 1** shows the results of necessary additional force to the parapet. By increasing the strength of parapet, the column ductility response can be less than the ductility capacity. But for 5-span continuous girder bridges which is heavier inertia force than others, the ductility capacity of columns is not satisfied only by increasing the strength of parapet. It means that the control of expansion gap between girder and abutments is necessary as the same time. In **Table 1**, thus obtained, the combination of necessary additional strength for parapet and expansion gap which will be satisfied the necessary ductility performance is shown.

**Table 1** Necessary Strength and Expansion Gap for Parapet

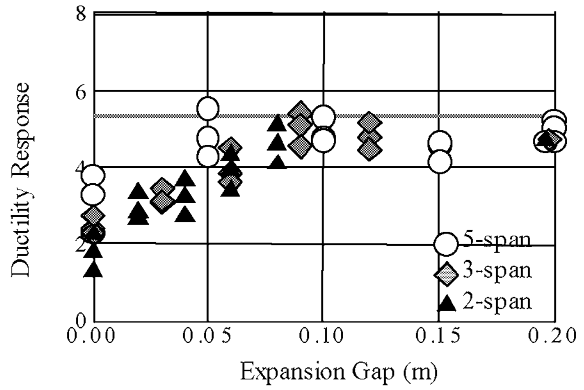
| Ground Type | Bridge Model | Necessary Strength for Parapet (Necessary Additional Strength) | Obtained Appropriate Expansion Gap (Ratio to Original Design) |
|---|---|---|---|
| 1 | 5-span | 20,000kN (+9,000kN) | 50mm (50%) |
| | 3-span | 20,000kN (+9,000kN) | 60mm (100%) |
| | 2-span | 11,000kN (0kN) | 40mm (100%) |
| 2 | 5-span | 40,000kN (+29,000kN) | 50mm (50%) |
| | 3-span | 20,000kN (+9,000kN) | 60mm (100%) |
| | 2-span | 11,000kN (0kN) | 40mm (100%) |
| 3 | 5-span | 40,000kN (+29,000kN) | 50mm (50%) |
| | 3-span | 30,000kN (+19,000kN) | 60mm (100%) |
| | 2-span | 20,000kN (+9,000kN) | 40mm (100%) |

### 4.4 Effect of Expansion Gap between Girder and Parapet

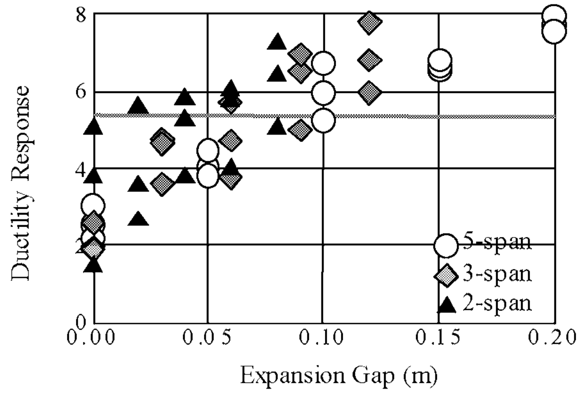
To study the effect of the expansion gap between girder and parapet. Parametric analyses are made. In the analysis, the expansion gaps are assumed as standard gap and 50%, 150%, and 200% of the standard gap as well as enough gap with no collision.

**Fig.10** is shows the relation between the gap and ductility response of columns. It is found that by strengthening parapet and the controlling the gap appropriately, the response can be restrained less than the ductility capacity. In the largest response case such as the case of ground condition of Type 3 (soft ground), by decreasing the gap to 25% to 50% of usual design distance, the seismic performance can be satisfied.

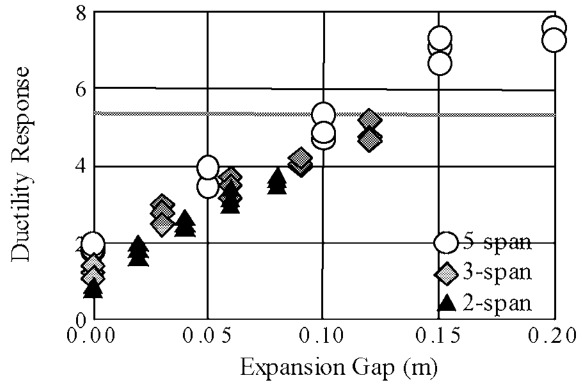
There are several ideas to control the expansion gap. The elongation of girder, reinforced concrete jacketing of girder, use of damper-stoppers and so on are one of examples.



(a) Ground Type 1



(b) Ground Type 2



(c) Ground Type 3

**Fig.10** Relation between Expansion Gap and Ductility Responses of Columns

## 5. CONCLUSIONS

To develop the seismic performance evaluation methods of a whole bridge system considering the abutment and backfill soils, the earthquake response behavior is studied through parametric anaylses. The following results are obtained as:

1) The restraint effect of abutment and backfill soils on the longitudinal displacement response of girders is significant. Therefore, the effect should be appropriately considered in the seismic evaluation of existing bridges.

2) Abutment and backfill soils may be modeled as simplified model consisted of single-degree-of-freedom model and the slip-type spring with enough accuracy to obtain the whole bridge displacement response behavior.

3) To enhance the seismic performance of bridges, by appropriately designing the expansion gap between girder and parapet and the parapet strength, the response of bridges can be effectively controlled. There are several methods to control the expansion gap by the elongation of girder, and use of damper-stoppers and so on.

4) In the analyses of abutment and backfill soils, the reliability of reaction characteristics and dynamic behavior of abutment is key issues [6]. The behavior is planned to be experimentally verified and the effective seismic retrofit measures of a whole bridge system considering the abutment restraint effect is to be proposed.

## REFERENCES

1) Japan Road Association: References on Seismic Design of Highway bridges, 1997.3 (In Japanese)

2) Ogura, Y. and Unjoh, S.: Dynamic Behavior of Abutment subjected to the Collision Effect of Girder, Proceedings of the Symposium on Earthquake Engineering, JSCE, 2003.12 (In Japanese)

3) Japan Road Association: Design Specifications for Highway Bridges, Part. V, Seismic Design, 2002.3 (In Japanese)

4) Kawashima, K.: Study on Collision Modelling for Dynamic Analyses, Journal of JSCE, No. 308, pp.123-126, 1981 (In Japanese)

5) Kobayashi, H., Unjoh, S. and Nishioka, T.: Study of Seismic Retrofit considering the A Whole Bridge Systems with Abutment at Both Girder Ends, Proceedings on Symposium on Seismic Design of Bridges based on Ductility Design methods, 2004.1 (In Japanese)

6) Romstad, K., Kutter, B., Maroney, B., Vanderbilt, E., Griggs, M, and Chai, Y., H.: Experimental Measurement of Bridge Abutment Behavior, UCD-STR-1, 1995. 9