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EARTHQUAKE RESISTANT DESIGN OF BRIDGE CONSIDERING LATERAL MOVEMENT

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ABSTRACT

In this study, the stress and deformation of a superstructure and abutment under lateral movement is examined and an adequate analytical model of these states is considered in the dynamic analysis of the whole bridge system. The improvement of the bridge's seismic performance is inspected based on the analytical results. In this case, the input seismic wave is set as a level 2 earthquake, and two types were used. Type I (plate boundary type) has numerous repetitions at an acceleration of approximately 400 gal, while Type II (inland direct strike type) has fewer repetitions but a stronger acceleration at 800 gal.

Introduction

With bridges built on soft ground (clay), lateral movement of the clay, caused by the fill behind the abutments occurs, causing damage to expansion joints, supports, and other parts. In addition, abutment parapets and superstructures come into contact, causing increased axial force on the superstructures, leading to their damage. Presently, when various organizations in Japan design bridges, they investigate the potential of lateral movements (Specifications for Highway Bridges, Part IV, 2002). As such, they work to strengthen pile foundations, improve clay layers, and take other preemptive measures to reduce the occurrence of lateral movements in advance. Therefore, in the early stages of construction, lateral movements are now seldom seen. However, since the lateral movement of clay occurs over a long period of time, displacement happens gradually, a decade after construction, and negatively effects the functionality of the bridge. When this phenomenon occurs, it is handled by replacing expansion joints and supports, repairing parapets, and taking other measures.

However, in Japan, which is a country with frequent earthquakes, design for massive earthquakes, including level 2 tremors on the Japanese scale, is necessary. The fill behind abutments is judged to contribute to the ability of suppressing vibrations of bridges. As such, designs anticipating the effects of this backfill are now conducted. With bridges in which lateral movements occur, the clearance with the movable side is eliminated and direct contact is made with the superstructure. Thus, it is said that earthquake resistance is enhanced since it is more likely to be affected by the backfill effect.

In these ways, the lateral movement of the abutment has both positive and negative effects on bridge structures. This paper will attempt to look at the enhancement of earthquake resistance and clarify this

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enhanced effect through analysis. The bridges are modeled, in which lateral movements occur and clearance is eliminated, causing the superstructure and a parapet to make contact, and compare this to an ordinary state.

Lateral movements are displacements in the horizontal direction caused by the deformation of the clay layer from the increased load of the fill behind the abutments. As the clay deforms in a horizontal direction, it pushes the pile foundation of the abutment, causing the abutment itself to ultimately lean forward. This occurs on both the fixed and the movable sides. And, as this displacement is absorbed by the movement of the supports on the movable side and the limit is exceeded, contact is made between the parapet and the superstructure. Furthermore, if the displacement is larger, the supports on the fixed side are destroyed and the function of the bridge itself is then lost. Thus, since the observable phenomena differ according to the degree of lateral movement and analyzing them all at once is difficult, this study will focus on cases in which the movable side parapet and the superstructure come into contact, which is currently the most frequent phenomenon. More so, in order to recreate the lateral movement effect accurately, the ground displacement, foundation displacement, and abutment displacement will be considered as initial conditions. However, since the lateral movement effect changes with time, there are many questions such as when this should be examined and how these displacement conditions should be handled during kinetic analysis. For this reason, this study only consider the relative displacement of the superstructure and the parapet.

Overview of the Subject Bridge and the Analysis Model

Overview of the subject bridge

Key traits of the subject bridge

The bridge that was the subject of this study was designed according to the Specifications for Highway Bridges, Part I-V (2002), and is a single-span bridge as shown in Fig. 1. The design includes steel plate girders for the superstructure, an inverted T type abutment (RC structure) for the substructure and a steel-pipe pile foundation. The ground is comprised of an alluvial gravel layer (N value > 40) around a depth of 15 m, and then gravel with an N value of about 20, and above that, an accumulated soft clay ground. The primary features of the bridge are shown in Figs. 1 and 2.

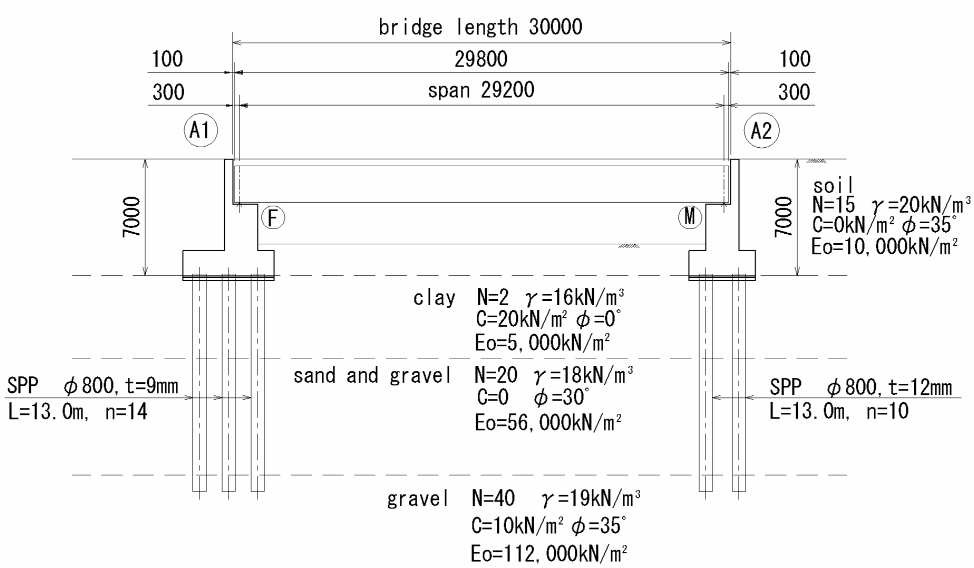


Figure 1. Bridge parameter.

Bridge conditions used in the analysis

In ordinary bridge design, the necessary clearance must be obtained to prevent contact between the superstructure and the parapet during an earthquake (Fig. 3 (a)). However, if lateral movement occurs, the abutment will lean and the clearance on the movable side will be eliminated, resulting in contact between the superstructure and the parapet (Fig. 3(b)). In order to model these conditions, the spring was set at the contact position between the superstructure and the apex of the parapet (point A in Fig. 3(b)), and the lateral movement effect was examined. The next section covers the details of this model analysis.

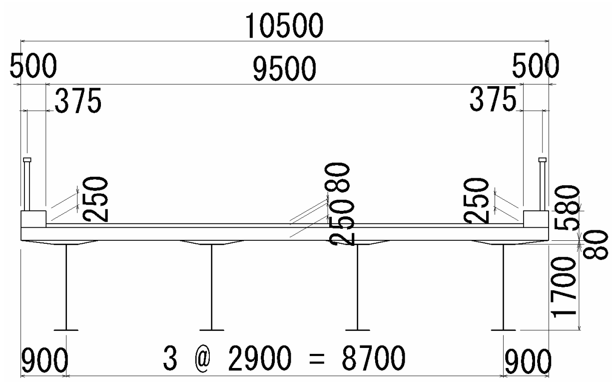
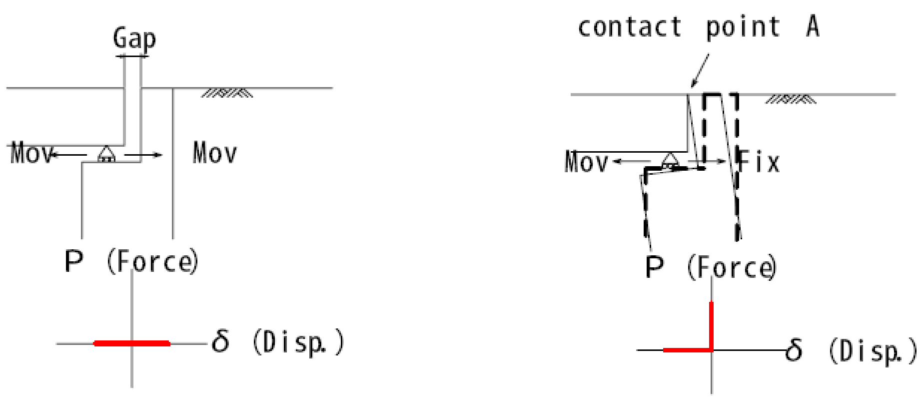


Figure 2. Superstructure shape.



(a) normal condition (case-1) (b) lateral movement model (case-2)

Figure 3. Image of lateral movement.

Details of analysis

Analysis method

Since the lateral movement effect is mainly in the bridge axis direction, a two-dimensional framework model in the bridge axis direction only was used. Since it is supposed to withstand a level 2 earthquake movement, the members should all be nonlinear. However, at this initial stage of research, rather than an exact solution, it was decided to seek results as an elasticity response that is easy to understand. In order to investigate the causes and to determine the characteristics of the members, a linear model was set with members being elastic or equivalent in rigidity, which made the analysis results easy to understand. The model used in this analysis is as shown in Fig. 4.

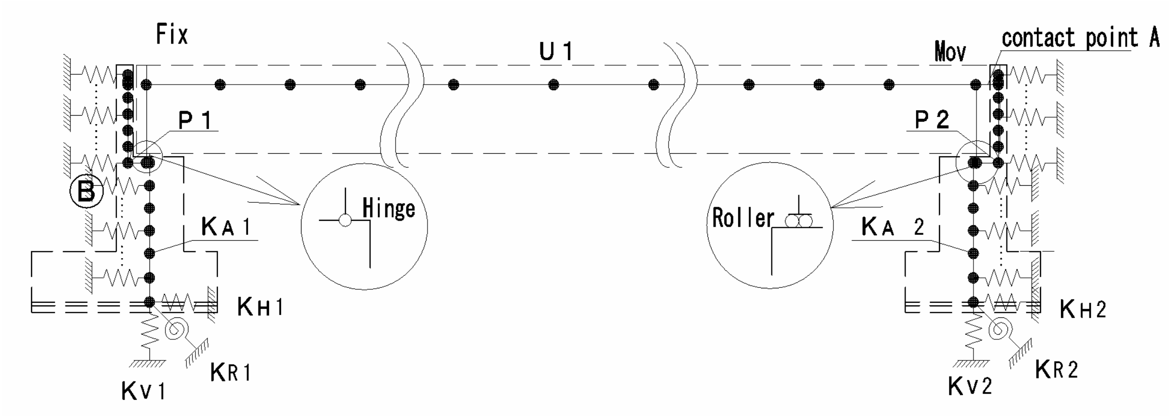


Figure 4. Analysis model.

Characteristics of members

Each member is set as fundamentally linear or equivalent to linear as described above. The superstructure is elastic, the parapets and abutment breast walls are linear equivalents with yield rigidity, and the foundation is elastic. These were set as the vertical, horizontal, and rotating spring elements at the pile heads. Furthermore, since the conditions of the reinforcements of the parapets differ between the front and the backsides, a model with a slope change from left to right was used. The various characteristics of each member are shown in Table 1 (superstructure and substructure) and Table 2 (foundation). In addition, regarding backfill resistance, since setting the damping effect becomes difficult when modeled with equivalent rigidity, the upper limit of passive earth pressure with a bilinear model was expressed. Table 3 shows the various factors.

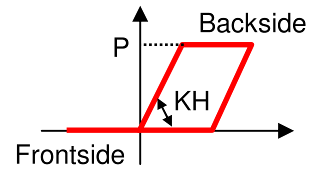
Table 1. Superstructure and substructure parameters.

Parameters		Elastic modulus	Geometarical moment of inertia	Inertia (yielding)	Area	Shear modulus of rigidity
Sign		E	I_0	I_y	A	G
Unit		KN/m^2	m^4	m^4	m^4	kN/m^2
Superstructure		2.0*10^8	0.109	-----	0.186	7.7*10^7
Parapet	Backside	2.0*10^7	0.110	0.0140	5.25	1.1*10^7
	Frontside			0.0096		
Wall		2.0*10^7	7.000	0.5873	21.0	1.1*10^7

Table 2. Foundation parameters (Elastic).

Spring name	Sign	Unit	Spring value	
			Fixed side	Movable side
Vertical Spring	K_V	MN/m	4,052	3,964
Horizontal Spring	K_H	MN/m	1,389	1,047
Rotation Spring	K_R	MN/rad	1,612	1,327

Table 3. The upper limit of passive earth pressure with a bilinear model for back soil resistance.

Parameters	Sign	Unit	Value	Model chart
Elastic modulus	E_0	KN/m^2	42,000	
Coefficient of subgrade reaction	K_H	KN/m^3	11,326	
Coefficient of passive earth pressure	K_{EP}	-----	4.527	
Initial inclination	$KH = K_H*B*Hi$			
Upper bound value	$P = 1/2*\gamma\ *Hi^2*K_{EP}*B$			

*Footnote: B: depth(m), Hi: set height of spring(m) ,γ : unit weight of soil(kN/m^3)

Model of contact parts

The contact condition of the superstructure and the parapet was assumed to be one of two cases—when there is clearance between them and when they are in contact. In Case 1, when there is clearance, the superstructure can be displaced freely in either direction (Fig. 5 (a)), while in the Case 2, when the superstructure and the parapet are in contact, the superstructure can move freely in the direction away from the parapet, but is restrained in movement toward the parapet (Fig. 5 (b)).

Input seismic wave

The input seismic wave was set as a level 2 earthquake, and two types were used in accordance with the Specifications for Highway Bridges, Part V (2002). Type I (plate boundary type) has numerous repetitions at an acceleration of approximately 400 gal, while Type II (inland direct strike type) has fewer repetitions, but a stronger acceleration at 800 gal. Specifically, three of each type, as shown in Table 4, were used. Details about these waveforms can be found in the Specifications for Highway Bridges, Part V (2002).

Table 4. Kind of earthquake wave used for analysis (Ground type II).

Wave Type	Record place	Earthquake name	The maximum acceleration
Type I	①Itajima Bridge LG	Hyuganada(1968)	362.6 gal
	②Itajima Bridge TR		384.9 gal
	③Onneto Bridge TR	Hokkaido-toho oki (1994)	364.8 gal
Type II	①JR Takatori NS	Hyogoken-Nanbu(1995)	686.8 gal
	②JR Takatori EW		672.6 gal
	③Osaka Gas Fukiai N27W		736.3 gal

Results of Analysis and Discussion

Next, the results of the two cases described in 2.2 (3) that were compared are explained and discussed. The parts that should be focused on when considering lateral movement in an ordinary design are the superstructure (U1 in Fig. 4), where increased cross-section force can be expected, the abutment breast walls (fixed and movable bases: KA1 and KA2 in Fig. 4) and the parapet base on the movable side (P2 in Fig. 4).

Furthermore, since six different seismic waveforms were used, after considering the effects of each seismic wave, the Type I and Type II waves with the greatest effects were selected and considered for each investigation item.

Tendencies of different seismic waves

Superstructure (U1)

The maximum value of the axial force affecting the superstructure for each seismic wave is plotted in Fig. 5. This figure shows the Case 2 results of the occurrence of axial force, with an axial compression force of 1,300 – 2, 300 kN m. Among these, the seismic waves that are used when investigating the superstructure cross-section later are I-1 and II-2, which had the maximum axial forces among Type I and Type II waves, respectively.

Bottom wall areas (KA1, KA2)

Fig. 6 (a) and (c) are plots of the fixed side response bending moment maximum values, and Fig. 6 (b) and (d) show the same results for the movable side. In these figures, Case 1 and Case 2 are shown together, making the following results clear.

1. Compared to Case 1, the response value in Case 2 is smaller. This can be thought to be due to the beneficial effects of backfill resistance and energy absorption, as well as energy absorption by the parapet.
2. The tendencies of the seismic waves in both Case 1and Case 2 are similar, with the seismic waves with the maximum values being I-1 and II-2 (Case1), among Type I and Type II (Case2) waves, respectively.

Parapet base (P2)

Fig. 7 shows plots of the maximum values of response bending moment from the seismic waves at the movable side parapet base. These values change the cross-section force. The sizes of the response values are smaller than at the wall bottom edge, but the tendencies for both Case 1 and Case 2, and by seismic wave, are the same, with the maximum values occurring in I-1 and II-1 for Type I and Type II waves, respectively.

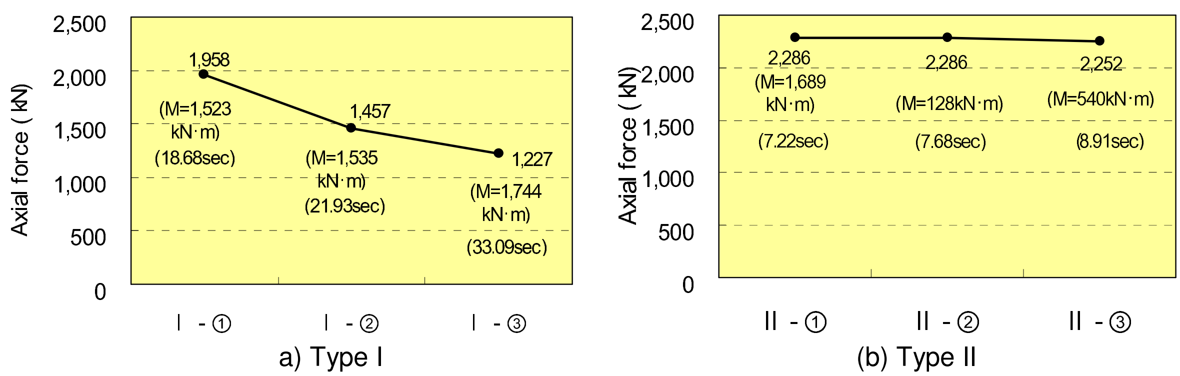
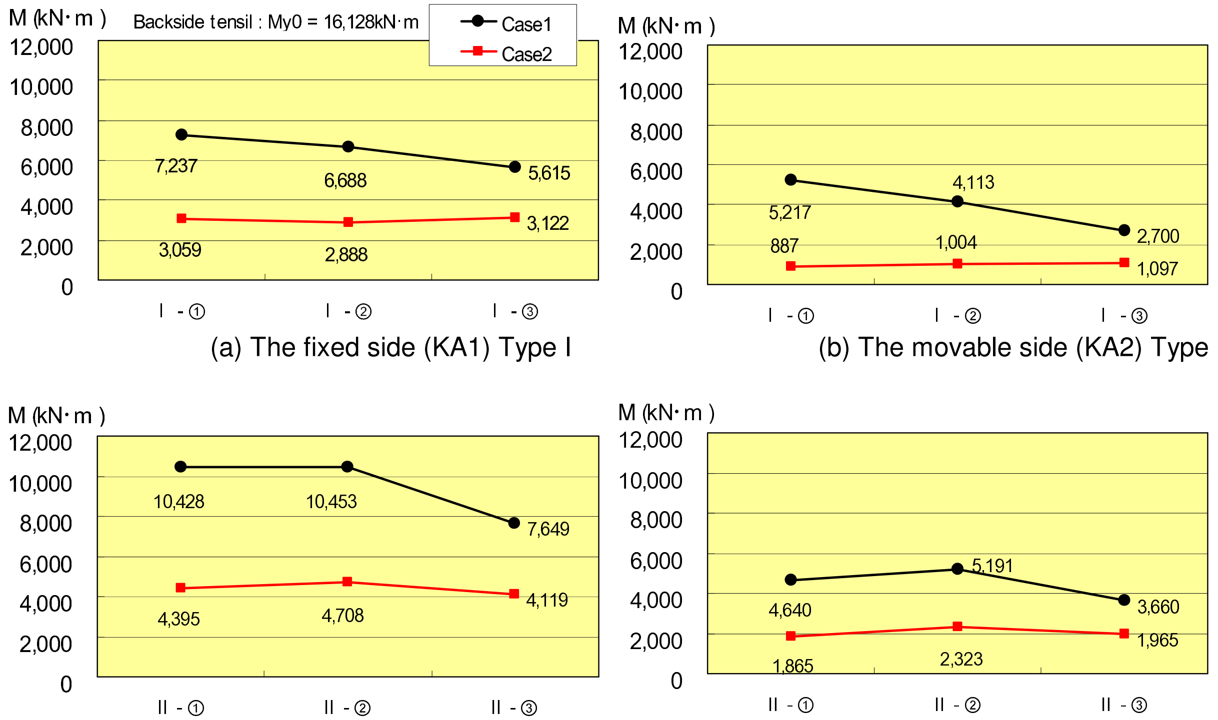


Figure 5. The maximum value of the axial force affecting the superstructure.



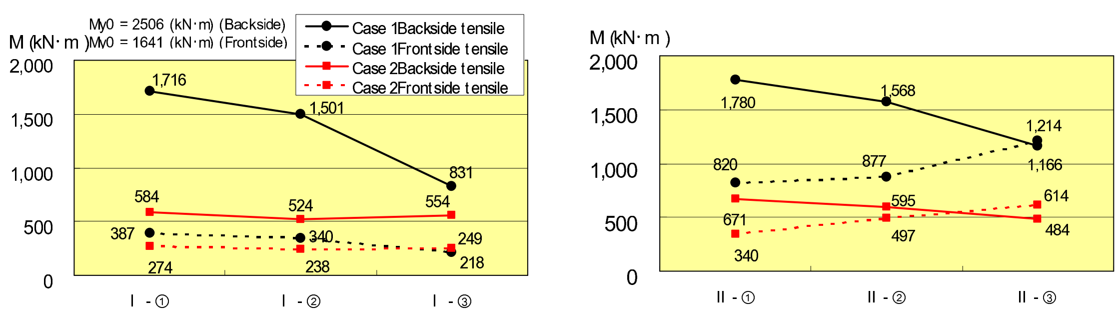
(a) The fixed side (KA1) Type I

(b) The movable side (KA2) Type I

(c) The fixed side (KA1) Type II

(d) The movable side (KA2) Type II

Figure 6. Plots of the fixed and movable side response bending moment maximum values.



(a) The parapet (P2) Type I

(b) The parapet (P2) Type II

Figure 7. Plots of the parapet response bending moment maximum values.

Evaluations of each part

Superstructure

Table 5 shows the loads on the superstructure and stress measurement results for the main girders. This table includes results from both normal conditions and earthquake conditions (the subject of this investigation).

According to the same table, the axial force and bending moment increases from the earthquake force are apparent, but the stress measurement results show that even when the axial force increases during earthquakes, the value is still within its capacity. It is supposed that the reason for this is that some increase in axial force and bending moment during an earthquake has no effect since the active load effect reaches 50% in the superstructure during normal conditions. Given this, it is concluded that there are no problems for the superstructure even when considering the effect of lateral movement during an earthquake.

Table 5. The loads on the upper construction and stress measurement results for the main girders.

Check item		Normal condition	Earthquake condition (This investigation)	
			Type I - ①	Type II - ②
Bend moment (kN·m)	Live load	3,349	-----	-----
	Dead load	3,514	3,514	3,514
	Inertia force	-----	1,523	1,690
	Total	6,863	5,037	5,204
Axial force (kN)	(Compressive)	-----	1,958	2,286
Stress (N/mm^2)	Tensile	201	186	198
	Compressive	91	109	107
Allowable stress (N/mm^2)	Tensile	210	315	315
	Compressive	210	315	315

*Footnote: the above-mentioned result is U1 (Fig.4) part.

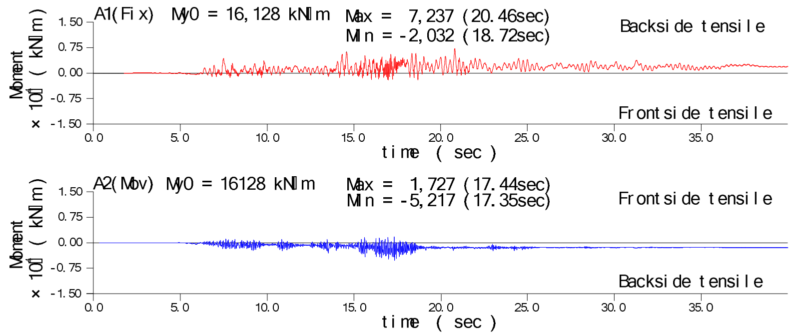
Wall base

The bending moment changes over time for the seismic waves chosen in 3.1 are shown in Fig. 8 (a) and (c) for the fixed side (Case 1: Type I and Type II), and (b) and (d) for the movable side (Case 2: Type I and Type II). The following conclusions are made from these figures.

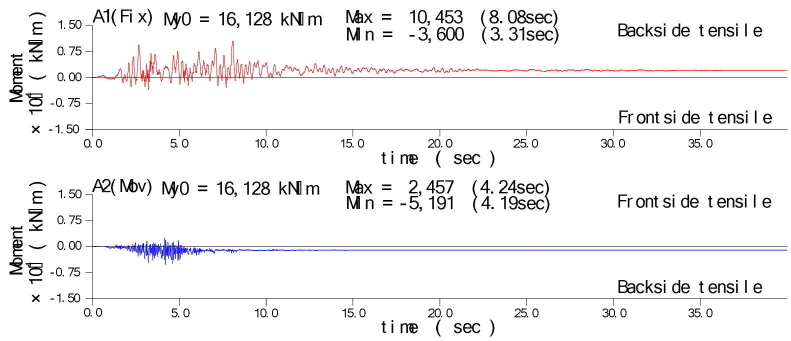
1. In every case, since there is abutment backfill resistance, the bending moment that makes the backside tense is great. Considering lateral movement, only in Case 2, in which a superstructure collision occurs, the bending moment that makes the front side tense is great from the time when the main movement finishes. (The direction of bending moment is reversed.)
2. Comparing Case 1 and Case 2, the response value itself is smaller in Case 2. This could be because of the reversal of the bending moment due to the effect of the superstructure load and the energy absorption of backfill and other elements.

Movable side parapet base

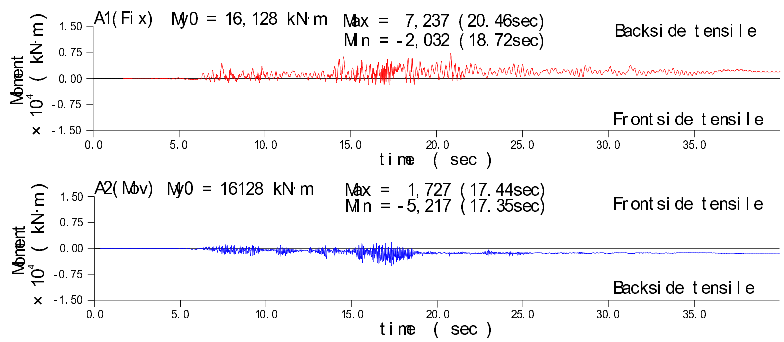
The cross-section force in the movable side parapet base increases only when the superstructure collides in Case 2. Fig. 9 shows the hysteresis curve (M–φ). The response for the front side, where there is no resistance, is large, while the response for the backside is small because, even though the load from the structure is significant, there is back resistance. The response value maximum in every case is smaller than the yielding moment, so the lateral movement effect can be said to be small. The reason for this could be due to the fact that normal designs are made based on earth pressure and that the load increase during an earthquake is small.



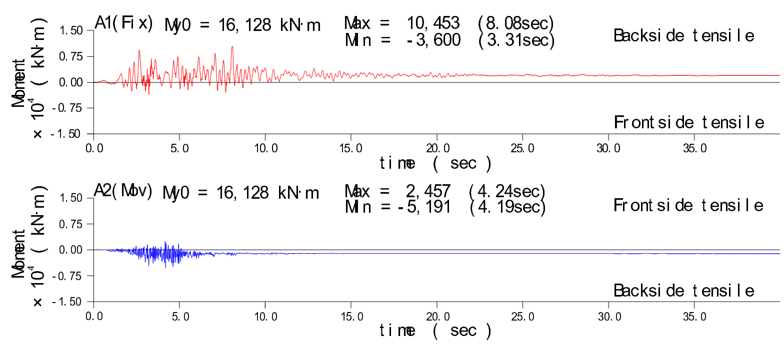
(a) Case 1 (Type I-①)



(b) Case 1 (Type II-②)

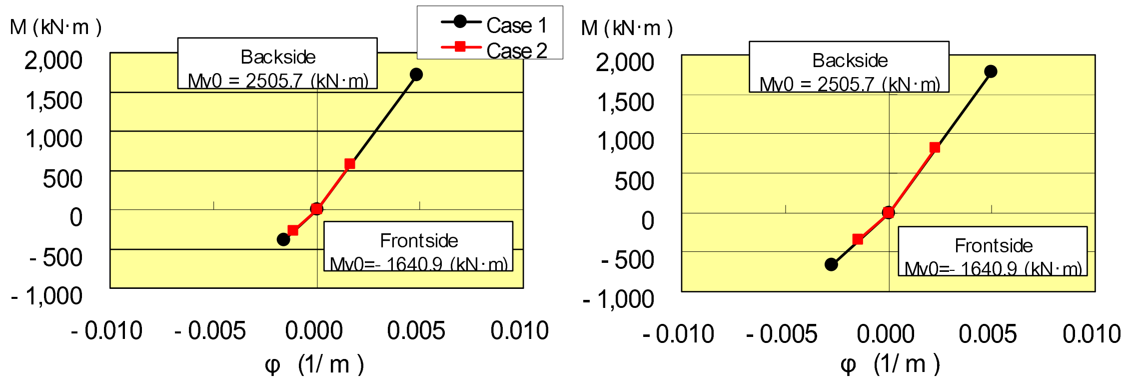


(c) Case 2 (Type I-③)



(d) Case 2 (Type II-②)

Figure 8. The bending moment changes over time for the seismic waves of the wall base.



(a) The parapet (P2) Type I-① (b) The parapet (P2) Type II-①

Figure 9. The hysteresis curve (M–φ) of the parapet response.

Conclusions

As a result of the analytical research on earthquake resistance of bridges, in which lateral movement occurs and their superstructures and parapets come into contact, it was found that for superstructures, parapets, walls (fixed and movable) and other members where effects were expected to be great, under the conditions of this analysis, earthquake resistance was actually enhanced. Furthermore, although not covered in this research, since the cross-section force at the wall bottom edge is reduced, the authors believe that there are no problems for the elastic foundation construction. The authors believe the main reason for this is the dispersion of the response value to the movable side abutment and the energy absorption of the abutment backfill.

The purpose of this research, which was to confirm the enhancement of earthquake resistance in bridges in which lateral movement occurs and the superstructure and the parapet come into contact, was achieved. However, since the results of this research are those from limited conditions and the research is in its initial stages, further research on a variety of issues is necessary in order to confirm the validity of these results and to determine quantitatively the extent of their applicability. These issues are as follows:

① Bridge sizes and types

② Input of earthquake force from the abutment backfill and the impact of mutual interactions between the abutment and the backfill

③ Initial abutment and displacement of pile foundations, and the effects of the increase of axial force on superstructures

④ Earth pressure effect during earthquakes

⑤ Effects of nonlinear members

Acknowledgments

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