EARTHQUAKE-RESISTANCE OF FOUR-SPAN CONTINUOUS PC RIGID-FRAME BOX GIRDER BRIDGE

Takahiro SAKATA[1], Takao NAKAZAWA[2], Ryuichi KANEMARU[3] And Mitsuo TOKUNAGA[4]

SUMMARY

The bridge, examined in this analysis, is a four-span continuous prestressed concrete, a frame-type box girder bridge with length of 410 meters; span proportion of 61+135+135+77 (m). It has piers of different height; 33, 104 and 33m. In Japan, one of the countries frequently struck by strong earthquakes, the sufficient earthquake-resistance of structures is required during and after construction. For continuous bridges with piers of different height, seismic forces act on each pier differently due to the difference in stiffness. When the stiffness of a shorter pier is increased, sectional forces tend to accumulate on it, thus, requiring a larger section. For an effective section of the bridge pier, the high strength reinforcement concrete bridge pier is the most appropriate for selected bridge model type. Nonlinear dynamic analysis is conducted for examining earthquake-resistance of the bridge with high strength reinforced concrete piers.

INTRODUCTION

The purpose of this paper is to determine the most suitable bridge pier type for a frame-type bridge with high piers and investigate earthquake resistance of the selected bridge model. In this study, four kinds of bridge piers (Reinforced Concrete, High Strength Reinforced Concrete, Steel Framed Reinforced Concrete, and Steel Pipe and Concrete Composite Structures) are selected and examined for construction costs. Due to the difference in stiffness, inertial seismic load acts on each pier differently. In the case of the bridge in this paper, lateral forces acted on end-side shorter piers are changed according to the stiffness of the longer pier located at center. Thus, the cost-effectiveness is needed to examine for the entire structural system having different combination of piers. Here, the cost-effectiveness is investigated for the six cases of different pier combinations. The nonlinear dynamic analysis are conducted to investigate earthquake resistance of the bridge with high strength reinforced concrete under two kinds of large earthquake (plate boundary type and inland directly below earthquake) also. From the results, firstly, it is found that the high strength reinforcement concrete bridge pier is the most appropriate selection for a bridge with high piers. Secondly, the earthquake resistance of the bridge with the high strength reinforcement concrete piers is validated under even large earthquakes.

GENERAL DESCRIPTION OF BRIDGE MODEL

The bridge has high bridge piers of 104 m (generally higher than 30 m). Superstructure is a four-span continuous prestressed concrete box girder with length of 410 m and width of 9.25m. It is composed of spans having different length (61, 135, 135, and 77m). This bridge is constructed at hard grounds. Figure 1 shows four-span continuous PC rigid-frame box girder bridge model.

[1] *CTI Engineering Co., LTD, Fukuoka Branch Office, Fukuoka, Japan Email: sakata@fukuoka.ctie.co.jp*
[2] *Department of Civil and Environmental Engineering, Miyazaki University, Miyazaki, Japan Email: nakazawa@civil.miyazaki-u*
[3] *Miyazaki Prefecture Office, Miyazaki, Japan*
[4] *Miyazaki Prefecture Office, Miyazaki, Japan*

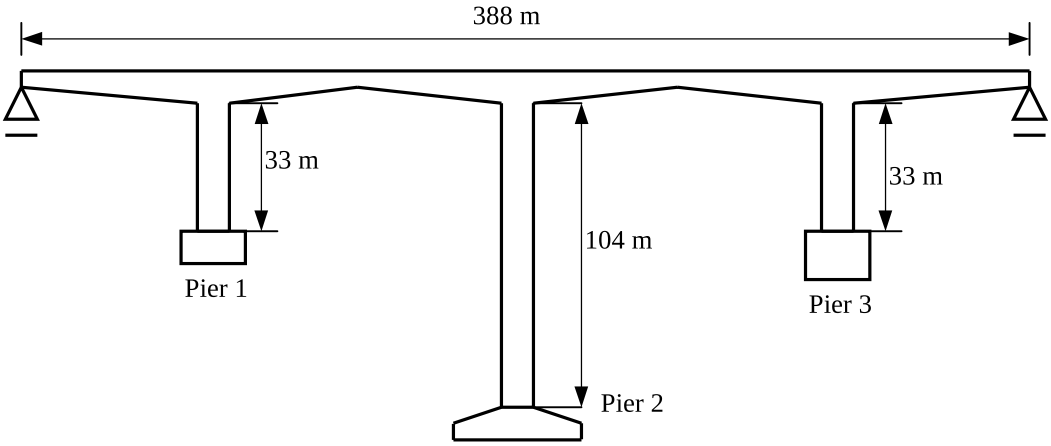


Figure 1: Four-span Continuous PC Rigid-frame Box Girder Bridge Model

INVESTIGATION OF BRIDGE PIER TYPE

Comparison of Construction Cost

In the case of the high bridge pier type, it is impossible to assure the verticality of the reinforced concrete piers by conventional methods, therefore, the steel framed reinforced concrete structure which uses H-steel beams in the piers was used generally as a guide. However, new construction methods has been developed for high bridge pier constructions, and it is possible to assure reduction of construction period, security under construction, and the construction has become more economical. In this paper, the new method of construction and conventional method are compared for Pier 2. From the results, it is found that the high strength reinforced concrete pier is most cost-effective for the high pier construction. Table 1 shows the comparison of construction cost for the selected pier types.

Table 1: Comparison of Construction Costs

Pier Type	Design Strength of Concrete	Yield Point of Steel Bar	Cost Ratio
Reinforced Concrete	30 (N/mm^2)	295 (N/mm^2)	0.87
High Strength Reinforced Concrete	50 ( )	685 ( )	*0.79
Steel Pipe and Concrete Composite	30 ( )	295 ( )	0.89
Steel Framed Reinforced Concrete	30 ( )	295 ( )	1.00

Comparison of Bridge Piers with Different Structural Members

It is found that Pier 2 with the high strength reinforced concrete is the most economical from the previous results. By the way, if Pier 2 is the reinforced concrete structure, Pier 1 and Pier 3 are undertaken by comparatively small lateral force due to large rigidity of Pier 2. Therefore, the effectiveness is needed to examine according to combination of piers having different pier type. Table 2 shows the combination of bridge piers with different structural type. In comparison of CASE-1 and CASE-2, the cost-reduction by Pier 2 with high strength reinforced concrete is more economical than the cost-reduction by Pier 1 and Pier 3 with the decreased section due to high rigidity of Pier 2 with reinforced concrete. As for CASE-3 and CASE-4, CASE-4 is more economical than CASE-3. Pier 1 and Pier 3 with high strength reinforced concrete are cost-effectiveness in the condition of the same structural type of Pier 2. Therefore, adapting high strength reinforced concrete for all piers is the most economical (CASE-4).

Table 2: Combination of Bridge Piers with Different Structural Members

P1,P3 P2	Reinforced Concrete	High Strength Reinforced Concrete
Reinforced Concrete	CASE-1	CASE-2
High Strength Reinforced Concrete	CASE-3	*CASE-4
Steel Pipe and Concrete Composite	CASE-5	CASE-6

ANALYSIS MODEL AND CONDITION

The bridge may have complex behaviors which are needed to design by dynamic analysis results. In this paper, after analyzing nonlinear pushover analysis, the possible plastic hinge was found. By using plastic hinge model the analysis model became more effective. The superstructure is considered as linear elastic material for simplicity. Table 3 shows the modeling of structural members. The initial force by dead load (after completing creep and shrinkage) is considered.

Table 3: Modeling of Structural Members

Structural Members		Analysis Model
Superstructure		Linear Elastic Beam Element
Bridge Piers	Upper	Nonlinear Rotation Spring
	Lower	Nonlinear Rotation Spring
	Others	Nonlinear Beam Element

Six earthquake waves are selected for analysis. It include two kinds of earthquakes; TYPE (plate boundary type earthquake) and TYPE (inland directly below earthquake). The ground spring is adopted to consider effects of ground displacements. Figure 2 represents the two earthquake waves representatively.

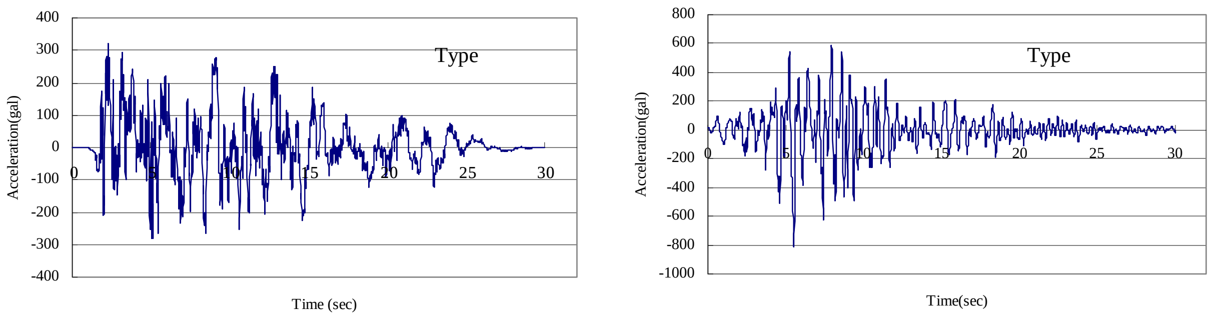


Figure 2: Earthquake Loadings Used In Analysis

NONLINEAR PUSHOVER ANALYSIS

In order to obtain a reasonable measure of the nonlinear earthquake behavior of frame-type structures without carrying out nonlinear time-history dynamic analysis, a pushover procedure is becoming increasingly necessary as a part of the design verification. However, this analysis can be used as the pre-analysis before nonlinear time-history dynamic analysis to investigate effects of axial force to the bending moment of structural members and to examine the procedure of plastic zone for frame-type structures. Figure 3 shows the relationship between lateral force coefficients and displacements for longitudinal direction. This analysis is nonlinear static analysis by increasing lateral force. This is the same as the relation P-δ of the bearing capacity method. The graph shows

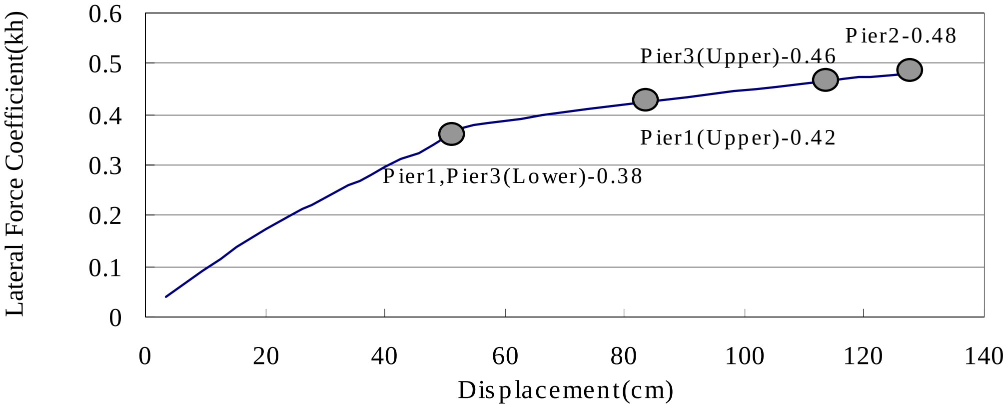


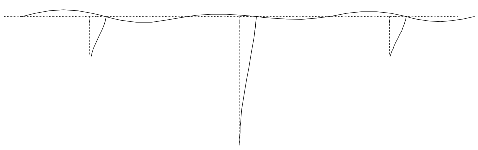
Figure 3: Lateral Force Coefficient - Displacement

that

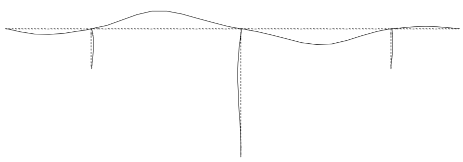
the ultimate condition of the bridge reaches after the yielding of Pier 2. The lower part of Pier1 and Pier 3 yield at lateral force coefficient 0.38. Then, after the upper part of Pier 1 yields the upper part of Pier 3 and Pier 2 will yield.

EIGEN VALUE ANALYSIS

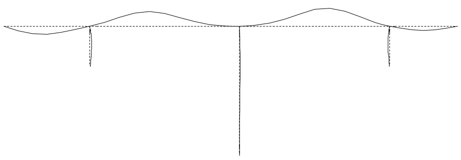
From eigen value analysis results, it is found that the selected bridge has comparatively long natural periods. The stiffness of the bridge piers used in this analysis are considered as full section rigidity. The natural period of the selected bridge model for the longitudinal direction is 1.82 second. Figure 4 represents natural frequencies and mode shapes for 1st, 2nd, 3rd, and 4th.



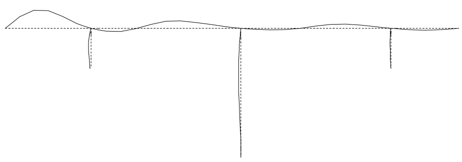
1st Mode (1.8201 sec)



2nd Mode (0.9635 sec)



3rd Mode (0.7942 sec)



4th Mode (0.5565 sec)

Figure 4: Natural Frequencies and Mode Shapes

NONLINEAR DYNAMIC ANALYSIS

Nonlinear Time History Analysis

In the case of a bridge with complex behavior during earthquakes, dynamic analysis shall be performed and its results may be reflected in the design of the bridge. The seismic coefficient method and the ductility design method are seismic performance calculation methods involving the replacement of dynamic seismic forces with static seismic forces, but not all cases of bridges with complex behavior during earthquakes can be fully represented by static analysis. The selected bridge may have complex behaviors due to long natural periods and or high piers, thus requiring dynamic analysis. The seismic behavior of the bridge during a strong earthquake is examined using nonlinear time history response analysis of two-dimensional frame model.

Analysis Results

There are nonlinear dynamic analysis results (displacement, acceleration, shear force, bending moment, hysteresis loop of plastic hinge) for each earthquake level from Figure 5 to Figure 9 representatively. Figure 5 shows displacement at top of Pier 2. The maximum displacement (0.33 m) occurs at 7.46sec and the minimum displacement (-0.30 m) occurs at 16.09sec for TYPE Ⅰ earthquake and the maximum displacement (0.23 m) occurs at 10.04 sec and the minimum displacement (-0.21 m) occurs at 6.98sec for TYPE Ⅱ earthquake. The residual displacements are small and do not the exceed allowable residual displacement (<1.04 m) as shown in Figure 5. Figure 6 shows acceleration at top of Pier 2. The maximum acceleration (2.73 m/sec^2) occurs at 6.25 sec and the minimum acceleration (-3.21 m/sec^2) occurs at 16.09sec for TYPE Ⅰ earthquake and the maximum acceleration (2.96 m/sec^2) occurs at 8.76sec and the minimum acceleration (-2.86 m/sec^2) occurs at 7.84 sec for TYPE Ⅱ earthquake. It is found that these acceleration responses are small. Figure 7 represents shear force at bottom of Pier 1. The maximum shear force (1488 tf) occurs at 7.48 sec and the minimum shear force (-1522 tf) occurs at 16.04 sec for TYPE Ⅰ earthquake and the maximum shear force (1010 tf) occurs at 9.93sec and the minimum shear force (-1389 tf) occurs at 7.1 sec for TYPE Ⅱ earthquake. These response shear forces do not exceed the allowable shear force. Figure 8 represents bending moment at bottom of Pier 1. The maximum bending moment (20510 tf-m) occurs at 16.09 sec and the minimum bending moment (-18120 tf-m) occurs at 7.47 sec for TYPE Ⅰ earthquake and the maximum bending moment (15980 tf-m) occurs at 7.05 sec and the minimum bending moment (-12850 tf-m) occurs at 10.06 sec for TYPE Ⅱ earthquake. These response bending moments do not exceed the allowable yielding moments. Figure 9 shows the hysteresis loop of plastic hinge at bottom of Pier 1. The pier enters the range of crack but do not yield. The dynamic responses for all piers show similar results to the results as mentioned above. From nonlinear time history analysis results, all bridge piers (high strength reinforced concrete) do not exceed the yielding point of the end side steel bars of the piers under even large earthquake loadings, and the other dynamic responses satisfy the allowable values too. It is found that the residual displacement do not the exceed allowable residual displacement (<1.04m) as shown in Figure 5.

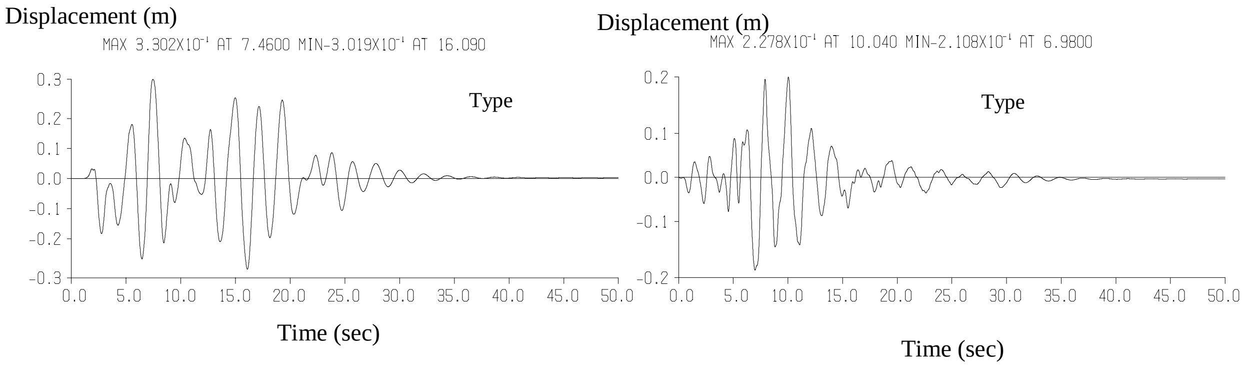


Figure 5: Displacement at Top of Pier

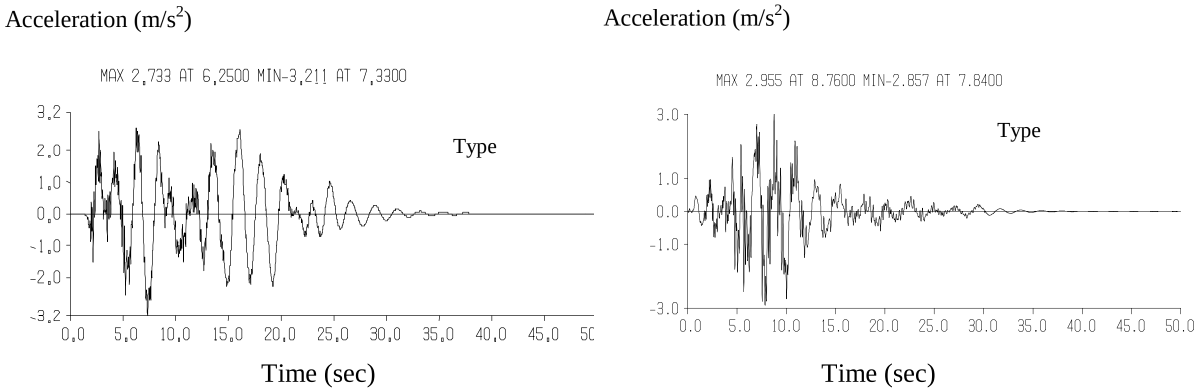


Figure 6: Acceleration at Top of Pier

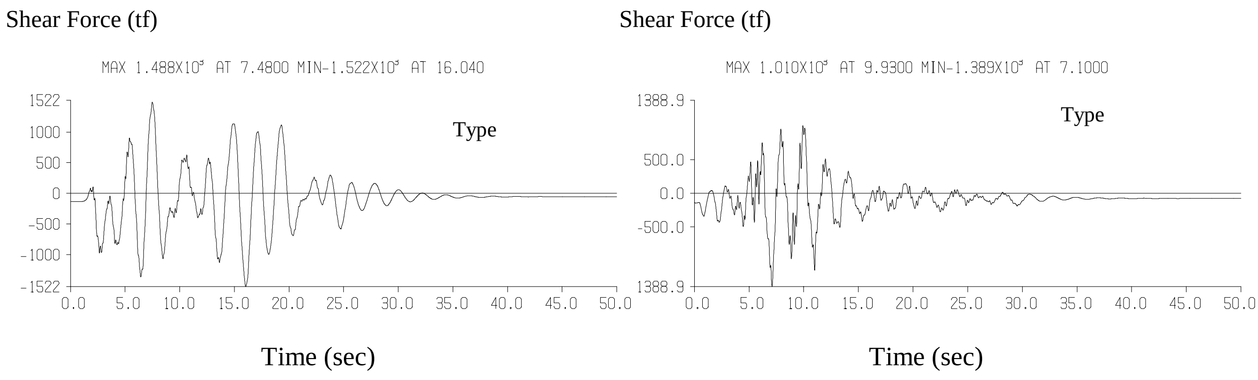


Figure 7: Shear Force at Bottom of Pier

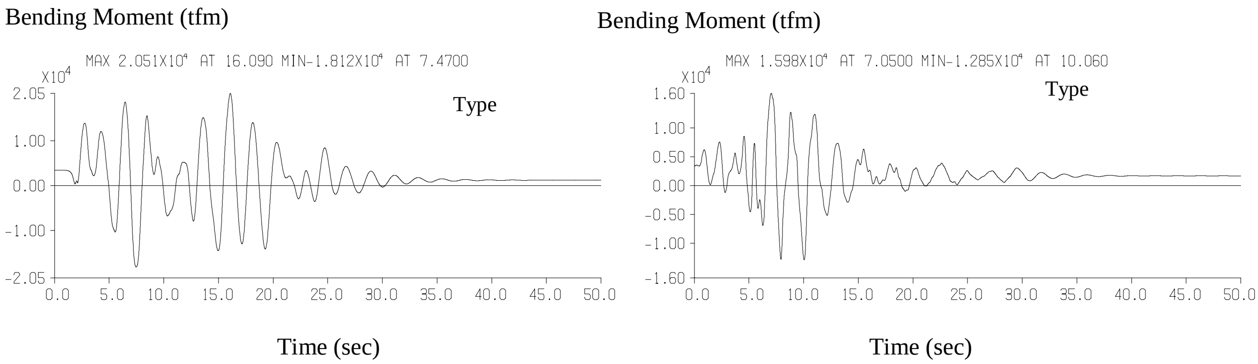


Figure 8: Bending Moment at Bottom of Pier

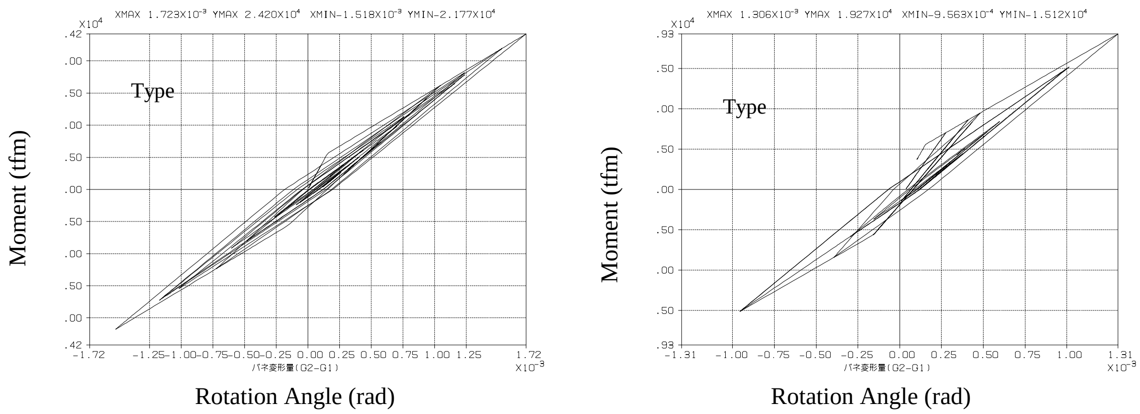


Figure 9: Hysteresis Loop of Plastic Hinge

CONCLUSIONS

It has been clarified in this study that effective earthquake-resistance of a continuous bridge with piers of different height is determined by the flexibility of piers and not by its strength or stiffness. As illustrated in the seismic design of this bridge, it is effective to use high strength materials in the bridge piers to increase flexibility or toughness. Therefore, the high strength reinforcement concrete bridge pier is the most appropriate selection for this bridge model type (frame-type concrete bridge with high piers).

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