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STUDY OF LEAD PILLAR DAMPER FOR THE EARTHQUAKE RESISTANCE REINFORCEMENT OF AN ESTABLISHED ROAD BRIDGE

Shinji Aramaki [1] Kiyoshi Uno [2] Katsuhiko Noyori [3]

SUMMARY

This study developed damper of a simple structure using the large lead of hysteretic damping. Static and dynamic examinations were conducted on the full-scale lead pillar damper, and the dynamics were characterized. Moreover, fatigue examination was performed and durability was confirmed. Nonlinear dynamic analysis was performed assuming attachment of the proposed damper to an established bridge. Consequently, the inertial force acting on a bridge pier could be largely mitigated. We confirmed that use of the lead pillar damper was effective as earthquake resistance reinforcement of an established road bridge.

INTRODUCTION

Two countermeasure methods exist for earthquake resistance reinforcement of an established road bridge. One improves the proof stress of a pier, and the other reduces the external force created by the earthquake. The former typical reinforcement method includes the steel lining method and the concrete jacket method. These methods of construction are inexpensive and easy to construct. However, if the pier is in a river, which requires a cut-off wall, construction may be costly. The latter method utilizes a seismic isolation bearing and a damper. When exchange to the seismic isolation bearing is necessary, a change in the vertical alignment of a road is needed because the bearing is thick. A seismic isolation bearing also is quite expensive. Therefore, a new damper is needed, which is more economical and inexpensive to repair, in addition to possessing suitable attenuation and stiffness.

This paper presents results of experiments using a full-scale lead pillar damper, and clarifies the dynamic characteristics and durability of the damper installed in a road bridge. Moreover, this lead pillar damper was attached to a pier built in 1975 that needed earthquake resistance reinforcement. Nonlinear dynamic analysis was performed and the vibration-mitigating effect of the damper was examined.

[1] Assistant, Kyushu Kyoritsu University, Kitakyushu, Japan, Email: aramaki@kyukyo-u.ac.jp
[2] Professor, Kyushu Kyoritsu University, Kitakyushu, Japan
[3] Office head, Toho Zinc Fukuoka Office, Fukuoka, Japan

2 OUTLINE OF EXPERIMENT

Specimen and examination method

Figure 1 shows the specimen. The lead material used was at least 99.99% pure, and consisted of a pillar (diameter of 120 mm, height of 340 mm) and an attachment (360 x 360 x 60 mm).

Figure 2 illustrates the experimental set-up. A hydraulic jack with a displacement amplitude of +/- 150 mm/maximum load of 101.5 kN was used to apply a horizontal load on the lead pillar damper through a roller bearing. A vertical load was applied to prevent the damper from rising. The vertical load capacity of the equipment used in this experiment was 294.0 kN. A load cell and displacement gauge were used to measure the load and displacement.

Testing included a static examination, dynamic examination, one direction load test, fatigue test, and a cyclic test. The specimen was vibrated by a sine wave as summarized in Table 1. The examination device allowed control of a single amplitude, therefore, the one-sided examination required speed adjustment by manual operation.

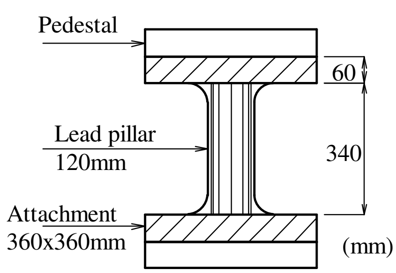


Figure 1 specimen

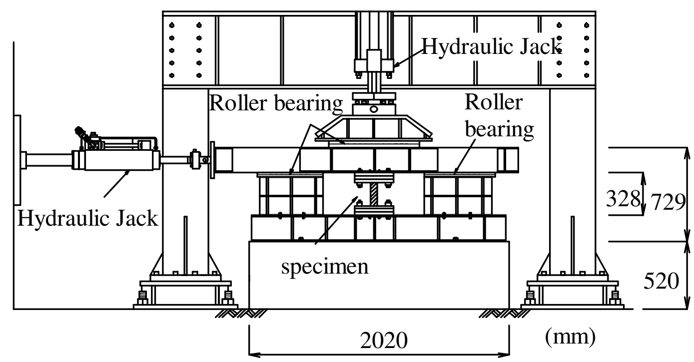


Figure 2 Experimental setup

Tabel 1 Test sketch

	Loading rate (Hz)	Maximum horizontal displacement (mm)
Static loading test	0.01	+/- 150
Dynamic loading test	1.00	+/- 50
One-directional loading test	0.01-0.02 (manual operation)	+ 300
Fatigue test	0.10	+/- 150 (50 cycles)
Cyclic test	0.10	+/- 150 (20 cycles)

Examination result

Static loading test

Figure 3 shows the results of the static loading test. Horizontal displacement occurs as the load gradually increases. The load displacement hysteresis curve is almost rectangular in shape and exhibited the behavior of a rigidly plastic body. After investigating the state of the specimen after an examination, some hollows were created in the pillar portion. However, no crack developed and the specimen remained intact and whole.

Dynamic loading test

Dynamic examination was performed to determine the influence of loading rate. However, an oil pressure jack cannot be operated finely enough to transform the specimen only by ±50 mm.

Figure 4 shows the results of the dynamic loading test. Generally, viscous force was influenced by loading rate with the viscous bodies, such as the lead material. Compared to the static examination results, shear force increases by about 1.5 times using the same displacement. However, the load displacement hysteresis curve assumes almost the same form as that from the static examination, indicating minimal influence of loading rate in the hysteresis characteristic.

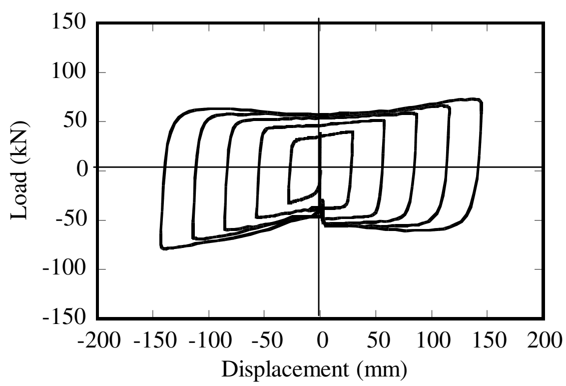


Figure 3 Results of static loading test

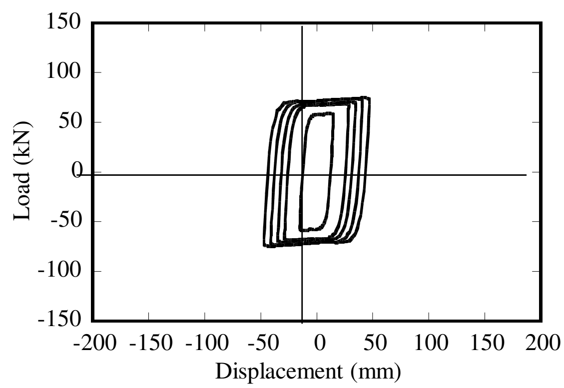


Figure 4 Results of dynamic loading test

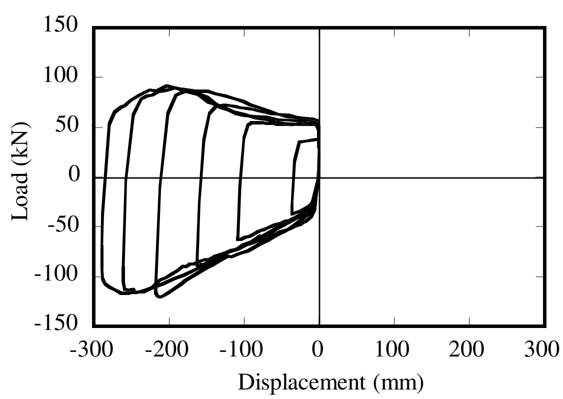


Figure 5 Results of one direction load test

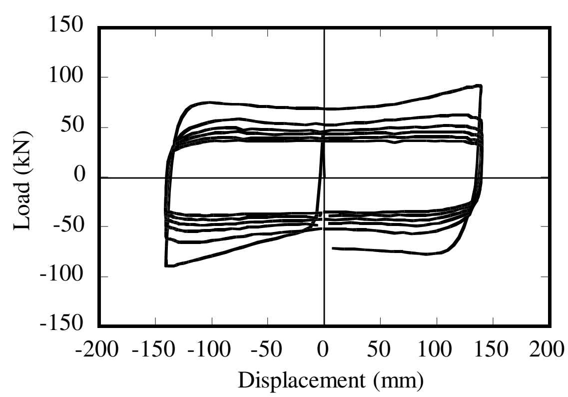


Figure 6 Results of fatigue test

One direction load test

Determining whether the response of the damper to the modification of 150 mm is enough can be accomplished by static examination. Therefore, a one-direction load test for checking the modifications was conducted.

Figure 5 shows the results of the one-direction load test. Load increased with an increase in displacement. However, load value reached a maximum (115.0 kN) when the specimen transformed it 230-270 m, and then, the load value decreased. These results indicate that when the damper is loaded at a speed of 0.01 Hz, the ultimate load is about 115 kN and ultimate displacement (strain) is 230 mm (0.68).

Fatigue test

Figure 6 shows the results of the fatigue test. Results of 50 cycle numbers are illustrated every 10 times. Figure 7 shows changes in load and displacement with time. Whenever the number of cycles increased, load decreased.

Figure 8 shows the relation of shear stress ratio to the number of cycles computed from the time history, expressed as a black dot. The stress of 35 cycle numbers declines until 40% of the first stage. The relation between tensile stress and lead temperature also is shown, which was changed to the relation between stress ratio and lead temperature, indicated by a white circle.

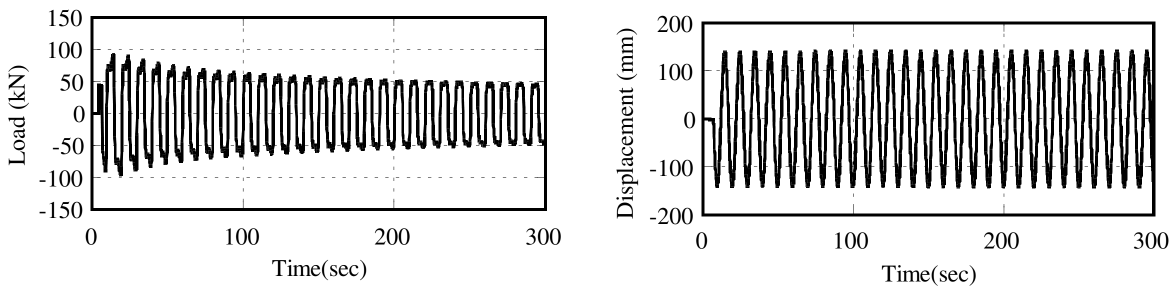


Figure 7 Results of fatigue test (time history)

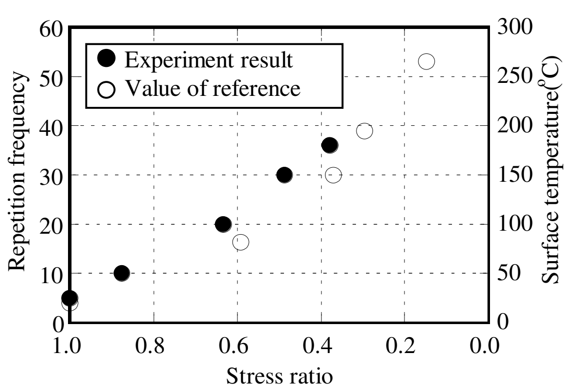


Figure 8 Results of fatigue test (relation of stress ratio to repetition frequency)"

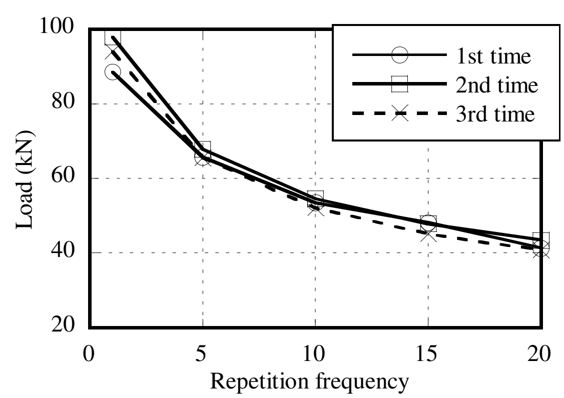


Figure 9 The relation of repetition frequency to load

The specimen surface temperature measured during the fatigue test was 76 Celsius at the 20th time frequency, and 150 Celsius at the 35th time frequency. The reference value and the value surveyed during the fatigue examination are in agreement. The decrease in stress was related to the rise in temperature.

One characteristic of lead is that a defect in the crystal lattice produced by plastic modification can be canceled by recrystallization at normal temperatures. Moreover, intensity decreases as the crystal grain becomes coarse. The dynamics of a lead damper are expected to change with the lead characteristics when an earthquake occurs. After moderate strength earthquake (maximum horizontal displacement of a bridge is approximately ± 150 mm), several aftershocks usually follow.

Therefore, multiple examinations were conducted to simulate aftershocks after an earthquake. The examination produced ±150 mm modifications in the lead damper 20 times. Then, the surface temperature of the damper was allowed to cool to ambient temperature, followed by another 20 displacement tests, and a delay to allow cooling to ambient temperature. This cycle was repeated a total of 3 times.

Figure 9 shows the examination results. In comparison with the 1st test, the 2nd and 3rd loads are relatively large. However, the relation between load and displacement does not differ greatly. The attenuation function of an initial state was confirmed. Therefore, the ability of the specimen to function as an earthquake-proof damper was verified.

3 HYSTERESIS CHARACTERISTICS OF LEAD PILLAR DAMPER

When performing the dynamic analysis of a bridge, the required characteristic values of a lead pillar damper include equivalent spring coefficient (Ke) and equivalent damping coefficient (he). Referring to the hysteresis curve of the load test shown in Figure 10, he and Ke are calculated using:

$$Ke = \frac{P}{S_{max}} \tag{1}$$

$$he = \frac{Wd}{4\pi \cdot Ws} \tag{2}$$

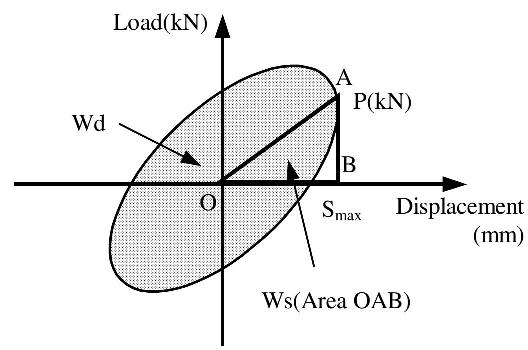


Figure 10 Hysteresis characteristics

where S_{max} is the maximum horizontal displacement, P is the horizontal load, Wd is the hysteretic energy of the damper, and Ws is the strain energy of the damper.

Results of tests using U-type lead dampers in a construction field are available. Therefore, the proposed hysteresis characteristics of the damper developed here and a U-type lead damper were compared.

The relation between equivalent spring coefficient and shear strain is shown in Figure 11. The equivalent spring coefficient decreases sharply until shear strain is 0.3, and then becomes a fixed value. In a dynamic examination (as compared to a static examination), the spring constant becomes large, indicating the influence of loading rate. Comparison with the U-type lead damper yielded almost equivalent results.

The relation between equivalent damping coefficient and shear strain is shown in Figure 12. The tendency for the equivalent damping coefficient to decrease is seen with an increase in shear strain. However, the equivalent damping coefficient is within the limits of 0.4-0.6, similar to that obtained from the static examination. In addition, test results were similar to those obtained using a U-type lead damper.

Figure 13 shows the relation between equivalent damping coefficient and the number of cycles, which reveals a trend toward an increase in equivalent damping coefficient with the number of cycles caused by the strain energy (Ws) being larger than reduction in hysteretic energy (Wd) of the damper. Proposed installation of the damper on the bridge estimated that the equivalent damping coefficient of the damper should be 0.4, determined from Figures 12 and 13.

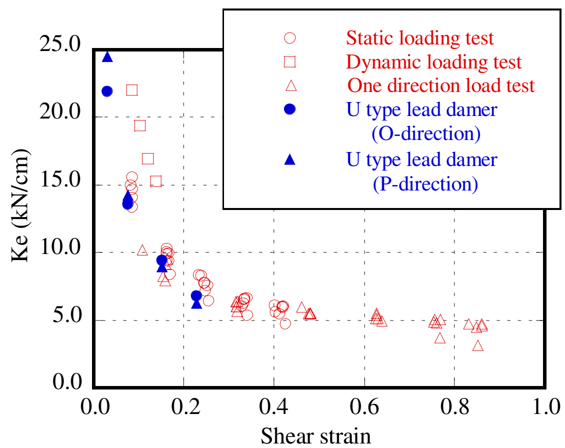


Figure 11 The relation of shear strain to equivalent spring coefficient

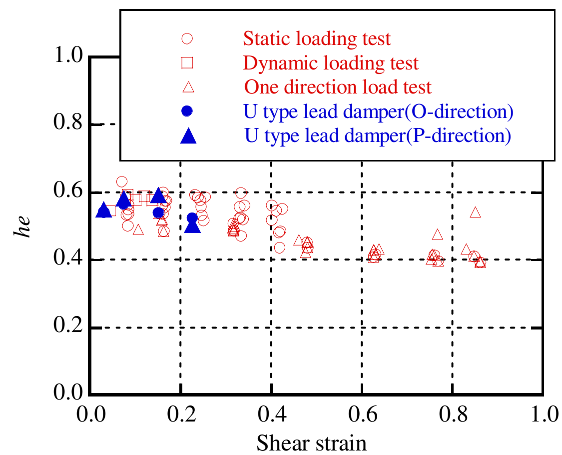


Figure 12 The relation of shear strain to equivalent damping coefficient

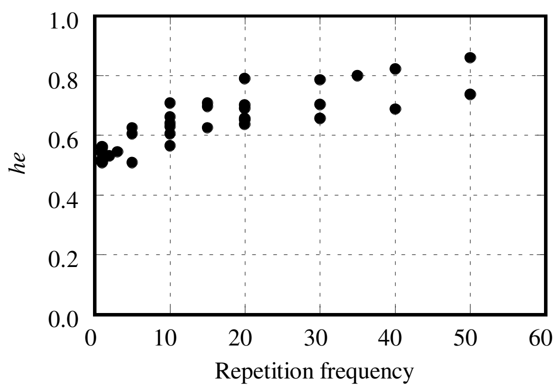


Figure 13 The relation of repetition frequency to equivalent damping coefficient

4 APPLICATION TO EARTHQUAKE RESISTANCE REINFORCEMENT

A bridge built in the Showa 50s requires earthquake resistance reinforcement. A damper was attached to these bridges to perform an analysis of earthquake resistance.

A bridge outline and an analysis model

A bridge outline and analysis model are shown in Figure 14. The analysis object was built in 1976 and is a PC pre-tension system simplicity connection T girder bridge. Only P1 pier fixes support the condition; other pier and bridge abutments are mobile. The analysis model used a linear beam element for the superstructure and pier. However, the plastic hinge domain of the pier base was used as the rotation spring, which renders the relation between bending moment and curvature nonlinear. The foundation spring used an equivalent alignment spring. The influence of abutments was not taken into consideration in the analysis.

The input seismic wave used three types of acceleration waveforms of type II that met the design specifications of highway bridges.

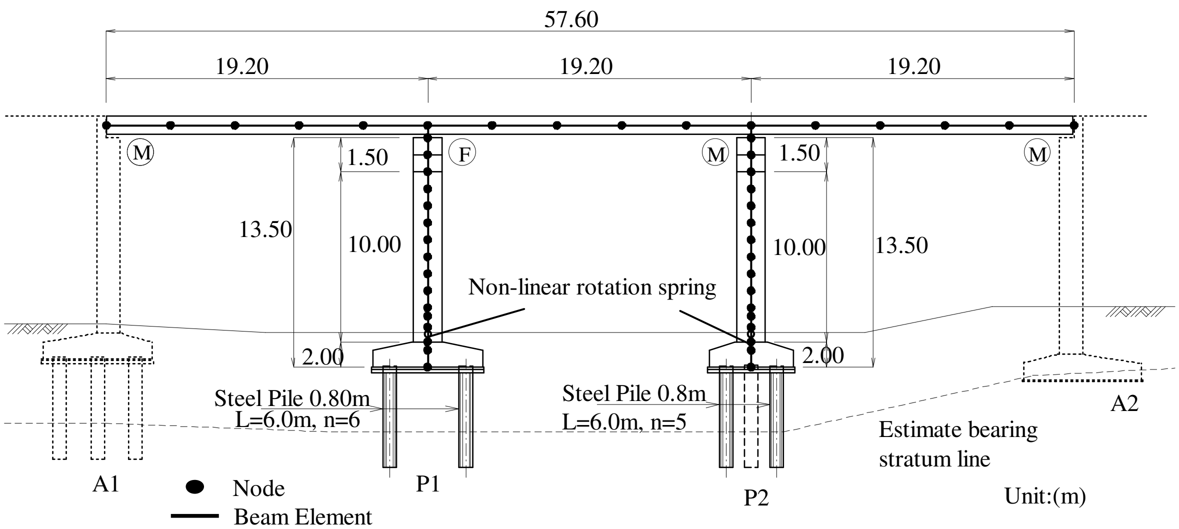


Figure 14 A bridge outline and an analysis model

Examination results

Three lead pillar dampers 120 mm in diameter were installed, for a total of six pieces in the positions of the abutments shown in Figure 14. The characteristic value of the damper from Figure 11 ,12 were used.

Figure 15 shows the time history of displacement position of the inertial force of the superstructure acting on P1 pier. In the P1 pier, the maximum grade decreased to approximately 50 percent due to the effect of the damper.

The relation of bending moment to rotation angle in the pillar base is shown in Figure 16. According to the effect of the damper, the inertial force acting on the pier is reduced. Therefore, before installation of the damper, the rotation angle of about the 2-time allowable value is the chosen value.

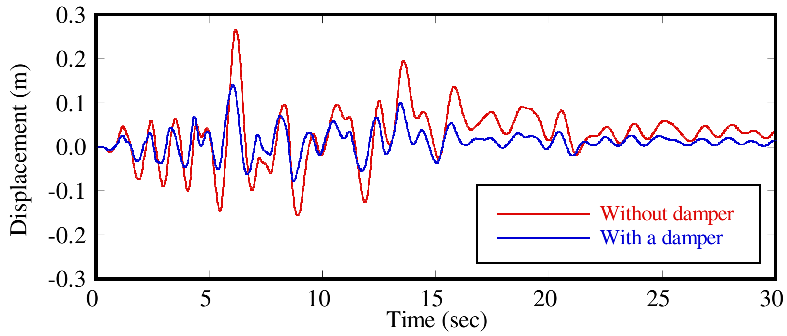
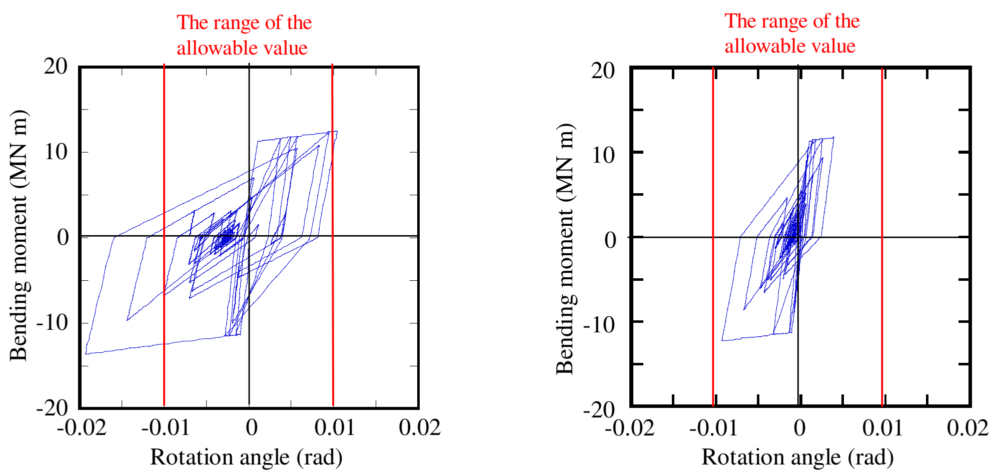


Figure 15 Time history (position of the inertial force of the superstructure acting on the pier)



(1) Without damper

(2) With a damper

Figure 16 The relation of bending moment to rotation angle

Table 2 The result of reference of the safety(P1 pier)

	Without damper	With a damper	Allowable value
Maximum displacement (cm)	27.64	13.36	
Maximum acceleration (gal)	311.5	394.4	
Maximum rotation angle (rad)	0.0196	0.0087	0.0097
Maximum shear force (kN)	2500	1696	2371
Remaining displacement (cm)	3.57	0.59	12.00

Table 2 shows the maximum response value of the P1 pier, including an evaluation of safety. Values in the table are averages of the maximum response value of three types of seismic waves. By installing the damper, as for the P1 pier, the natural frequency increases. The maximum acceleration increases as the displacement maximum decreases.

The safety of the pier was determined by the rotation angle and shear force of the pier base, and the remaining displacement of caused by the inertia force of the superstructure acting on the pier. All measurements indicated that the displacement decreased considerably due to the attenuation effect of the damper.
The displacement of a beam was similar to the displacement of a bridge pier under fixed conditions, 15 cm or less between the end of girder and abutments of the bridge. Thus, no damage is caused by collision of girder and abutments.

CONCLUSION

Experimental examinations and analyses were conducted to develop a lead pillar damper for earthquake resistance reinforcement of an actual bridge, which yielded the following results.

Although the displacement of the lead pillar damper (diameter of 120 mm, height of 340 mm) was 290 mm, no crack was generated in the pillar.

After 35 cycles of fatigue examinations, the temperature of the lead damper surface was 150 Celsius. Stress decreased by 40 percent of the first stage due to this temperature rise. In a damper exposed to the force of a moderate earthquake, the hysteresis curve of load and displacement was almost the same as that of the initial state, indicating the earthquake-proof characteristic of the damper.

Although the equivalent damping coefficient of the damper decreases as shear strain increases, it remained in the 0.4-0.6 range.

Installation of a lead pillar damper, even if it does not increase the ability of the bridge pier to withstand stress, has been confirmed to be safe on this bridge.

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