Design and Construction Highway Piers with Interlocking Hoops in Japan

Kazuyuki Mizuguchi[1)]
Norimasa Higashida[2)]
Koji Osada[3)]
Gaku Ohashi[3)]

1. Introduction

The Hyogo-ken Nanbu Earthquake of 1995 caused severe damages on various infrastructures, including highway bridges. From these experiences, Specifications for Highway Bridges now mandates in its structural detailed items section that bridge piers with a rectangular cross section should have an arrangement of intermediate hoop reinforcement at one-meter or less intervals in order to improve the deformation performance of the piers after they suffer plastic deformation. In addition, the end of hoop ties should be attached with hooks and secured to inside a bridge pier.

As Photo-1 shows, it results in such dense an arrangement that operatives cannot enter the concrete casting area, creating a problem in concrete quality management.

Bridge piers with interlocking hoops offer high restraining effects and help reduce the volume of reinforcing steel as well as enhance constructability. Starting around the mid-1970's, bridge piers having interlocking hoops appeared in California, USA, and the interlocking hoop reinforcement system was adopted by AASHTO in its standards in 1977 and by CALTRANS in 1990.

In Japan, a study on interlocking-hoop bridge piers began around 1997. In 1997, bridge piers with two interlocking hoops were built for the first time in Japan for the Trans Chubu Expressway constructed by the Japan Highway Public Corporation(JH). In 2001, reinforcement using four interlocking hoops was applied to wall bridge piers at the third work section in expressway construction. With the demand for lower cost and higher concrete quality getting greater, more use of interlocking hoops in bridge piers is expected.

This paper presents a summary of experimental results carried out by JH and others, and analyzes the applicability of bridge piers with interlocking hoops to typical expressways in Japan in terms of cost performance, constructability, and application range. Lastly, the construction of interlocking four hoops is introduced.

Photo-1 Example of arrangement of reinforcing bar

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1) Japan Highway Public Corporation Engineering Department Bridge and Structural Engineering Division

2) Japan Highway Public Corporation Hokkaido Branch

3) Japan Highway Public Corporation Expressway Research Institute Bridge Division

2. Study of the application of interlocking-hoop piers to road bridges on Japanese expressways

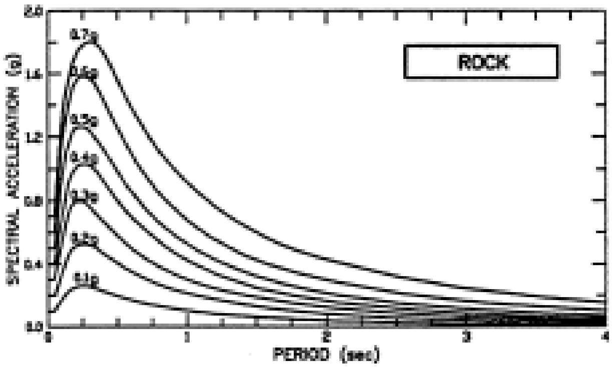
(1) Background behind common use of wall bridge piers in Japan

In both the U.S. and Japan, bridge piers with a circular cross section are considered to have greater deformation performance because they have greater restraining effects than those with a rectangular section. Reflecting this view, circular-section bridge piers are widely used in the U.S., while in Japan, the prevalence of wall bridge piers is still seen today even after introduction of the design method considering restraining effects. One of the circumstances behind this would be shown as follows:

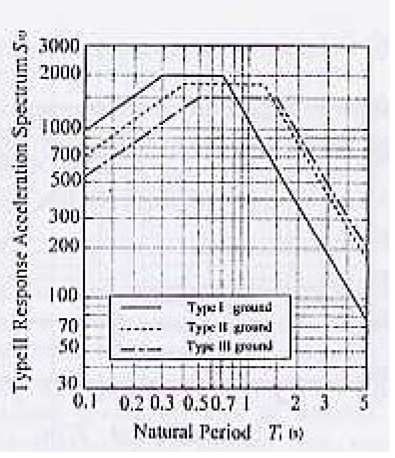
The values of seismic waves used for design calculations vary with countries since different countries assume different seismic motions and ground conditions. Figure-1 is a comparison example of response spectrum to seismic waves used in design process between the U.S. and Japan. As it shows, the U.S. data displays more conspicuous decline of response acceleration in the long-period range in the case of good soil. With rock, the peak acceleration occurs when the natural period is 0.1 second, and the longer the vibration period is, the smaller the response acceleration becomes. In Japan, even with the ground categorized as Class 1, the best ground condition, the acceleration stays at its peak, 2000 gal, with an increase in natural periods up to 0.7 seconds.

Thus, there is not much benefit for Japan to pursue a longer natural period in the direction perpendicular bridge axis as there is in the U.S. Due to this, in Japan, wall-type piers have been adopted more often than the multiple independent piers as a result of considering the foundation cost and the formwork cost for cross sectional areas of piers to obtain required bending strength.

Further, due to its difference from the U.S. in design approach to the allowable degree of damage to connections between super- and substructures of a bridge, Japan has seen a wider adoption of bridge construction method of separating the upper and lower works by installing rubber bearing. Moreover, wall bridge piers have a greater advantage in terms of the need to obtain a broader cross sectional area for bearing. This also has encouraged the use of wall bridge piers in Japan.



Response Acceleration Spectral Curves
from ATC-32 (ATC, 1996),
USA



Response Acceleration Spectral Curves
from Specifications for Highway Bridges,
Japan

Fig.1 Comparison example of Response Acceleration Spectral Curves between USA(ATC-32) and Japan(Specifications for Highway Bridges)

(2) Test results on expressway road bridges

Table-1 is a summary of the tests for interlocking-hoop/spiral bridge piers conducted by JH and others. Loading was performed in the direction perpendicular to the bridge axis as well as in the bridge axis direction. The subjected cross sectional areas range from 600 x 900 mm to 500 x 1300 mm. Tests with regard to interlocking hoop reinforcement were conducted also on wall bridge piers. The range of the shear span ratios, a/d, is between 1.9 and 5.0.

Table-1 Tests for interlocking hoop bridge piers conducted in Japan

Unit	Type of hoop	Section w*d (mm)	Shear span ratio a/d	Loading direction	Volume ratio of lateral restraining reinforcement (%)	Ultimate Ductility factor	Organization	Year	Legend in fig.2
1	2 hoops	900*600	5	bridge axis	0.19	7.2	JH	1998	●
2	2 hoops	900*600	5	bridge axis	0.29	8.4		1999	
3	2 hoops	900*600	5	bridge axis	0.52	7.1		1999	
4	2 hoops	1000*600	5	bridge axis	0.32	6	PWRI[1]	2000*	▬
5	2 hoops	850*600	1.9	perpendicular	0.46	11.9	JH	1997	■
6	2 hoops	850*600	1.9	perpendicular	0.23	8		1997	
7	2 hoops	850*600	1.9	perpendicular	0.12	8		1997	
8	2 hoops	600*400	3	perpendicular	1.04	9.9	Tanaka and R.Park[2]	1993*	◆
9	2 hoops	600*400	3	perpendicular	0.83	10		1993*	
10	2 hoops	600*400	3	perpendicular	1.11	12		1993*	
11	2 hoops	500*300	3	perpendicular	0.49	8.3	Yanagishita,Tanaka and R.Park[3]	2000*	
12	2 hoops	538*300	3	perpendicular	0.49	9.7		2000*	
13	2 hoops	500*300	4.8	perpendicular	0.49	8		2000*	
14	4 hoops	1300*500	6.4	bridge axis	0.31	9.8	JH	2002	▲
15	4 hoops	1300*500	6.4	bridge axis	0.51	10		2002	
16	4 hoops	1300*500	6.4	bridge axis	0.75	7.9		2002	

1) Public Work Research Institute Ministry of Construction : Study of simplified reinforcement, Pulic Work Reserch Institute Ministry of Construction

2) H.Tanaka, R.Park : Seismic Design and Behavior of Reinforced Concrete Columns with Interlocking Spirals, ACI Structual Journal, 1993.3-4

3) F.Yagishita, H.Tanaka, R.Park : Cyclic Behavior of Reinforced Concrete Columns with Spirals, Journal of Concrete Structures, 2000.11

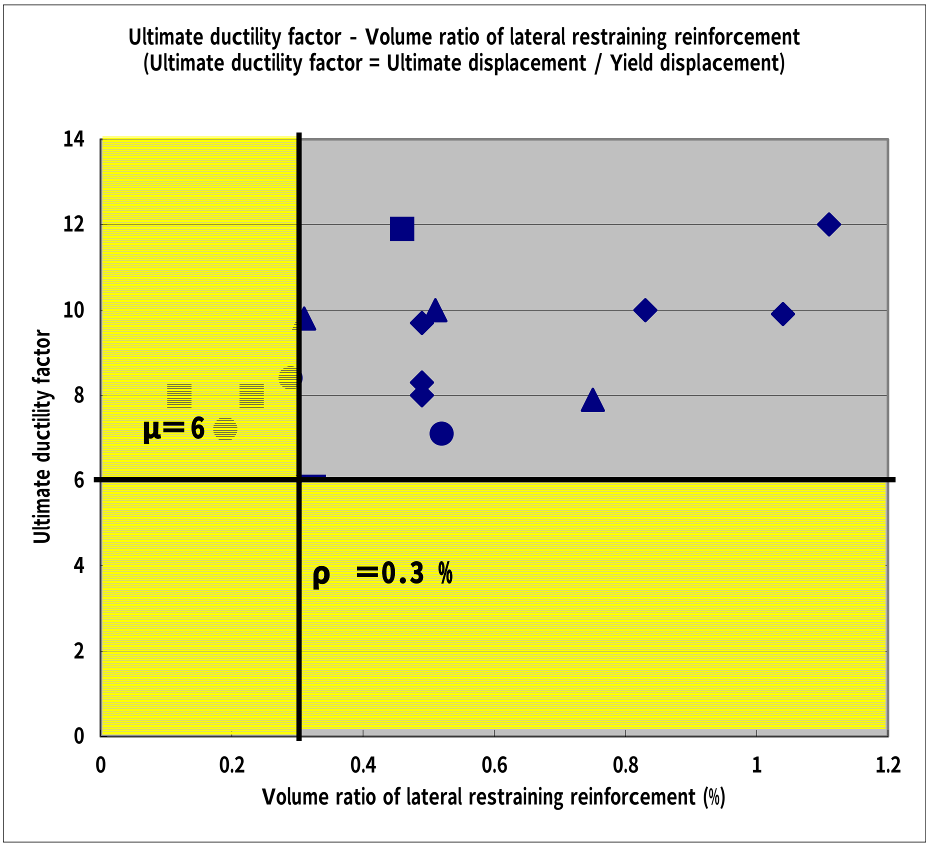


Fig.-2 Graph of the relation between hoop reinforcement ratio and ductility factor

Fig.-2 plots the relation between the hoop volume ratio and its ductility factor.

As can be seen from Table-1 and Fig.-2, the ductility factor of 6 or greater can be obtained when the center to center pitch of the hoops is less than 0.75 times the diameter of pier and the hoop volume ratio is 0.3% or greater.

From the result above, as far as interlocking-hoop bridge piers falling within the extent of the test above are concerned, we consider it acceptable to develop design on the assumption that the ultimate ductility factor, can be obtained as 6 at the minimum, if the center to center hoop pitch is up to 0.75 times the pier diameter and if the design satisfies the design details for improving ductility of RC piers of Design Specifications of Highway Bridges with the exception of the omission of intermediate restraining reinforcement.

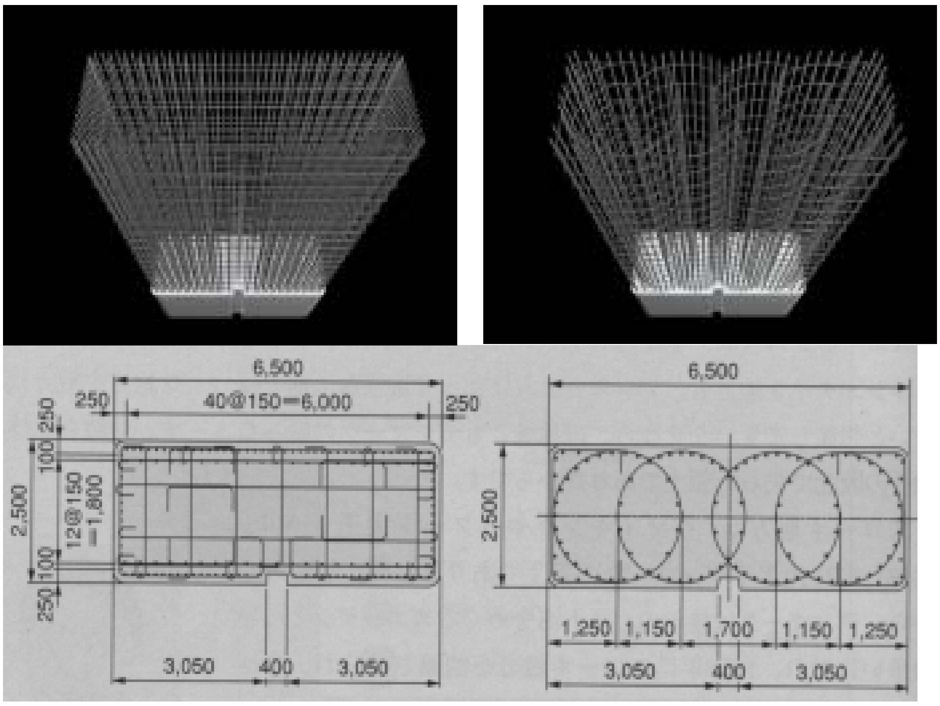
Furthermore, if it is mandated that the design should be based on the Standards mentioned above except for the calculation of the ultimate ductility factor, it will then necessitate designing the residual deformation volume as within 1/100 of the pier height in the light of ensuring their quick restoration performance when they are damaged. And as a result of this, check will be made in actual design tasks in order to ensure that excessive displacement will not be caused.

3. Economic effects of the application of the interlocking hoops to wall bridge piers

Table-2 compares the economic impacts when bridge piers with normal bar arrangement were changed to those with interlocking hoops. In this case, since the design details of the superstructure had been completed, we determined the volume of reinforcing steel in the axis direction in a manner that would produce the same ultimate strength before and after this change, in order to minimize the adverse effect on the foundation and superstructure of the alteration to the bar arrangement. Accordingly, we consider it possible to achieve a further cut in steel volume in the axis direction if the ductility improvement gained from adopting interlocking hoops can be reflected in the seismic design. Even though the ultimate bending strength of the steel is designed to be the same, it is possible to reduce the volume of hoops to about 60% of the steel for normal pier by omitting intermediate hoops and other means. Thus, the total work cost can be reduced by 10%. In the future, based on the result, we will study the range that will achieve cost reduction with the use of interlocking hoop reinforcement, and for bridge piers from which cost reduction can be expected, we think we will proactively work to change normal re-bar arrangement to interlocking spirals or hoops.

Table-2 Economic comparison when normal re-bar arrangement was changed to interlocking hoops

	Bridge pier with normal bar arrangement	Bridge pier with interlocking hoops	Interlocking /Normal
Sectional shape	6,500 x 2,500	6,500 x 2,500	-
Formwork (m^2)	306	306	0
The volume of longitudinal re-bar (t)	42.05	43.13	103%
The volume of lateral re-bar (t)	49.52	30.01	59%
Concrete volume (m^3)	276.25	276.25	100%
	¥17,100,000	¥15,400,000	90%



Normal bar arrangement Interlocking bar arrangement

Fig.-3 Example of changing the normal to interlocking bridge pier

4. Application range of bridge piers with interlocking hoops

1) Pier height

In many cases, bridge piers over 30 m in height are designed as a hollow pier in order to reduce the dead load. If the application of interlocking hoops is limited to piers with a hollow section, then if they are applied to piers exceeding 30 m, it may possibly require a larger-scale foundation due to the dead load. Consequently, it seems that the application range of interlocking hoops is limited to piers shorter than about 30 m.

For piers with less height, interlocking hoop reinforcement offers an advantage of obtaining high ductility. It cannot be said that this advantage is displayed, when bridge piers are too small in a/d. The lower limit of a/d in the past tests is about 2, and it seems appropriate that the application range of interlocking hoops should be 2 or greater in a/d.

Based on the above, we consider that the application range of interlocking hoop reinforcement in terms of pier height is generally between 5 m and 30 m.

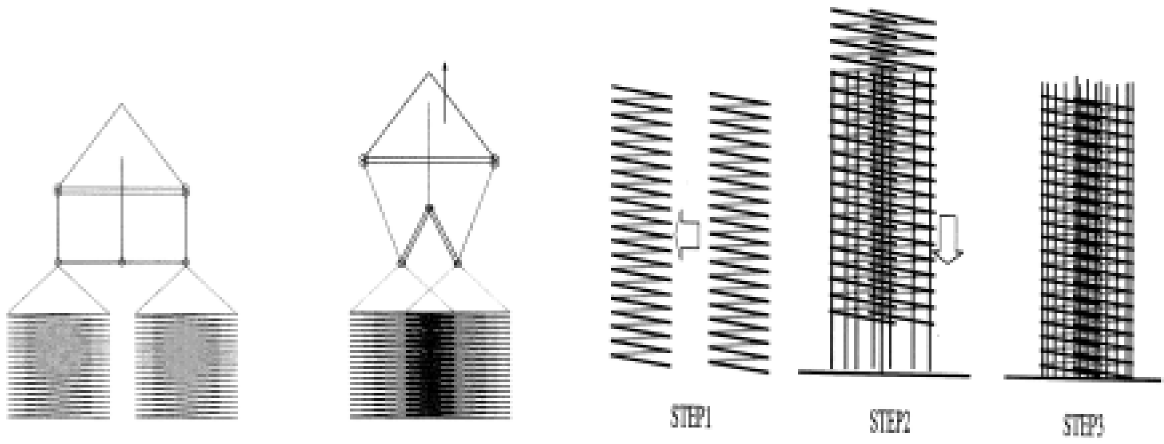
2) Sectional shape of pier

Although it is possible to attempt rationalization of re-bar arranging work by using spirals instead of hoops, it is difficult to fabricate spirals at the site, and when considering their transportation from the factory, the diameter is limited to 3.25 m or smaller. As described below, the maximum number of interlocking spirals in the direction perpendicular bridge axis, when they are used, is four for construction reasons, and if taking the center-to-center distance of the hoops as 75% of the pier diameter, the maximum interval in the direction perpendicular to the bridge axis becomes 10.56 m. Given the concrete cover over the re-bar, the maximum sectional area of the pier possible to be constructed using spirals is calculated as 3.5 m x 11 m. When exceeding this limit, the hoops need to be placed in two separate parts, considerably reducing the constructability.

In the case of a three-lane cross section and a PC single-cell box girder superstructure, the width of the lower floor slab is about 10 m. Even for bridge piers without overhang, it is possible to design them by using interlocking hoops.

5. Construction of bridge piers with interlocking hoops

Fig.-4 is a work flow diagram of placement status of spiral or hoops. As can be seen, hoops are put together while being suspended and then, keeping their position, are placed into the longitudinal reinforcing bars. Photo-2,3 shows the construction status of bridge pier with four interlocking spiral hoops. As can be seen, it was demonstrated through field application that rational construction of bridge piers with interlocking spiral hoops is possible when four or fewer hoops are used.



(1) Pattern diagram of adjusting center-to-center pitch of spirals

(2) Pattern diagram of placing spirals or hoops into the longitudinal reinforcing bars

Fig.-4　Pattern diagram of placement status of spirals or hoops

Photo-2　Construction status (1)

Photo-3　Construction status (2)