Economical Application Range of Interlocking Spiral/Hoop Reinforcement on Highway Bridge Piers

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Abstract

How much construction cost could be saved by rearranging lateral reinforcement of highway bridge piers from conventional rectangular hoops with cross ties to interlocking hoops or spirals was investigated through trial calculations.

In the calculations, ten bridge piers having different weight superstructures and different pier heights, which were already designed with conventional lateral reinforcement, were selected and re-designed for interlocking reinforcement. The total quantities of construction material before and after rearrangement were compared and the cost was estimated in each case. Details of interlocking reinforcement required for the design were also briefly discussed.

Finally, effective application pattern of interlocking reinforcement to highway bridge piers in terms of cost and detail were demonstrated.

Introduction

After the 1995 Kobe earthquake, the importance of lateral confinement of core concrete in bridge columns was highlighted yet again. For ductile response under severe earthquakes, a large amount of lateral reinforcement is required for better seismic design. Consequently, the congestion of reinforcing steel may cause not only an incomplete concrete casting but also an increase in construction cost due to the additional labor and steel.

Interlocking reinforcement is an effective scheme for reinforced concrete columns, providing effective lateral confinement due to the hoop tension effect, used extensively in California since the mid 70's[1]. Also in Japan, several highway bridge piers with interlocking reinforcement have been constructed[2] based on studies of the ductility and shear capacity of such columns conducted by many researchers in recent years[3].

However, in order to change the reinforcement structure of existing column designs to interlocking reinforcement, it is important to know in advance whether it is really cost saving, also taking into account the re-design cost.

In this paper, highway bridge columns with typical superstructures and different column heights were re-designed to have interlocking spiral/hoop reinforcement and the construction cost was calculated in order to study which case would be most effective. Based on the cost comparison, the economical application range of interlocking reinforcement to highway bridge piers was identified taking the details of reinforcement for design into consideration as well. Note that the effect of a reduced construction process is not calculated in the cost estimations.

Re-design target

Ten actual highway bridge piers to be re-designed were chosen from those planning to have different weight superstructures and different height piers. As the type of superstructure and its span length determine the dead load used in seismic design, the relationships between the weight of the typical five superstructures mainly used in JH projects and the span length were investigated as shown in Figure 1. Based on the results, the weight of superstructures for the target piers was categorized into three different ranges of approximately 4000kN, 8000kN and 12000kN. Three column heights were selected for cost evaluation at 10m, 20m, and 30m for each superstructure weight. Table 1 shows ten different bridge columns selected to meet these dead load and height combinations. Some did not meet the above specifications exactly.

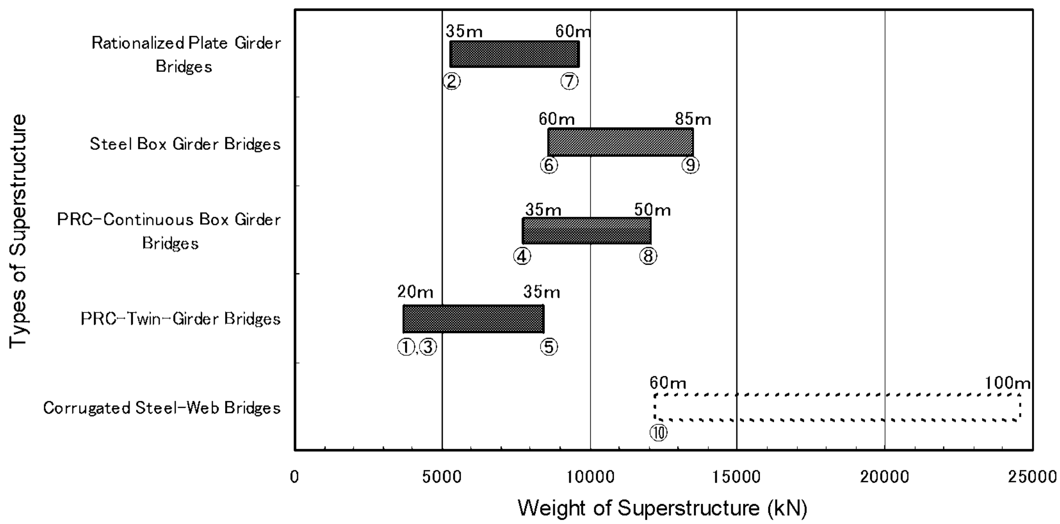


Figure 1. Relationships between weight of superstructure and span length

Table 1. Re-designed bridge piers

No.	Super Structure			Pier	Shear span to depth ratio		Cross section	
	Structure Form (system)	Span m	Estimated weight kN	Height m	Longitudinal	Transverse	Depth m	Width m
①	PRC-twin-Girder Bridges	22	4600	9.7	5.39	1.94	1.80	5.00
②	Rationalized Plate Girder Bridges	35	6963	10.0	4.55	2.00	2.20	5.00
③	PRC-twin-Girder Bridges	20	6502	15.0	5.00	3.33	3.00	4.50
④	PRC-Continuous Box Girder Bridges	22	8137	10.2	5.67	2.04	1.80	5.00
⑤	PRC-twin-Girder Bridges	25	6340	15.5	6.20	3.10	2.50	5.00
⑥	Steel box Girder Bridges	60	10787	12.3	3.51	2.46	3.50	5.00
⑦	Rationalized Plate Girder Bridges	53	7400	38	11.88	8.09	3.20	4.70
⑧	PRC-Continuous Box Girder Bridges	50	10434	8.3	2.37	1.66	3.50	5.00
⑨	Steel box Girder Bridges	85	11600	16.5	6.60	2.54	2.50	6.50
⑩	Corrugated Steel-Web Bridges	52	15200	27	7.71	4.50	3.50	6.00

Re-design procedures

Re-design procedures from conventional reinforcement to interlocking spiral/hoop reinforcement are summarized in Figure 2. They follow the Japan Road Association design code for strength and deformation capacities for road bridges[4)]. Reinforcement details such as the distance between the centers of the adjacent spirals/hoops and the minimum number of rebars placed in the interlocking region follow the Caltrans bridge design specifications[5)]. The minimum volumetric confinement ratio of 0.3% is derived from the test results carried out by JH and others[2)].

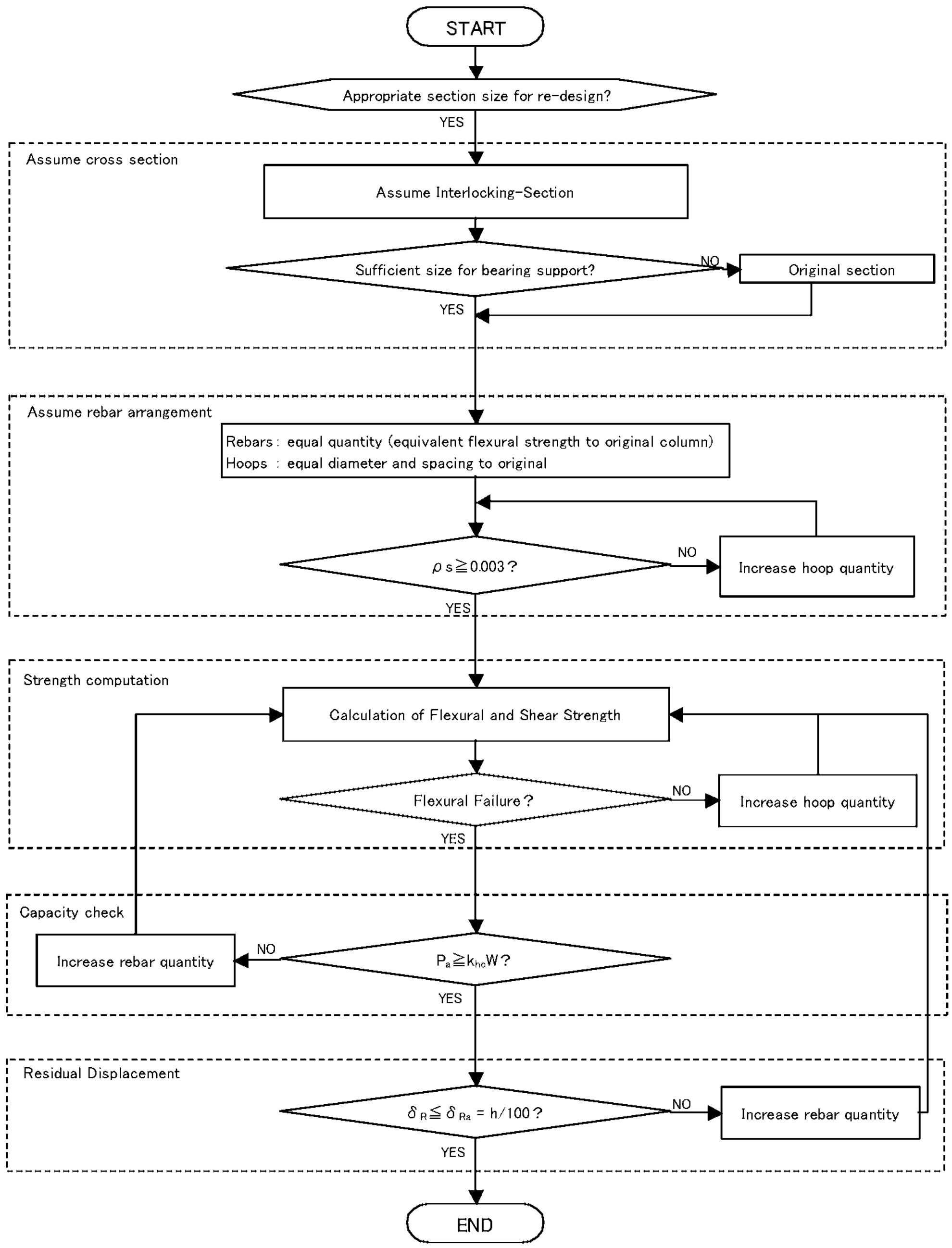


Figure 2. Re-design procedures

Details of reinforcement

The target bridge piers have solid (not hollow) rectangular cross sections where two to four interlocking spirals/hoops could be placed. According to the Caltrans design code for the distance between the centers of the adjacent spirals/hoops (0.5~0.75 diameter of the spiral), the aspect ratio of such cross sections is calculated as shown in Table 2.

Table 3 demonstrates the minimum spacing of reinforcing steel required in the JRA design code. Both longitudinal and lateral reinforcements should be fabricated with appropriate spacing in accordance with the bar diameter.

Table 2. Section aspect ratio

Number of hoops/spirals interlocked per section	Cross section aspect ratio		
2	1.50	～	1.75
2～3	1.75	～	2.00
3	2.00	～	2.50
4	2.50	～	3.25

Table 3. Minimum spacing of reinforcing steel

Bar size	40mm minimum	4/3 of maximum aggregate size	1.5 bar diameter	Required spacing	C to C distance	C to C distance (at lap splice)	For design (mm)					
							100	125	150	200	250	300
D13	40	34	23	40	55	70	○	○	○	○	○	○
D16	40	34	29	40	59	78	○	○	○	○	○	○
D19	40	34	35	40	64	87	○	○	○	○	○	○
D22	40	34	40	40	67	94	○	○	○	○	○	○
D25	40	34	46	46	77	108		○	○	○	○	○
D29	40	34	52	52	87	121		○	○	○	○	○
D32	40	34	58	58	97	135			○	○	○	○
D35	40	34	63	63	105	147			○	○	○	○
D38	40	34	69	69	115	161				○	○	○
D41	40	34	75	75	125	175				○	○	○
D51	40	34	92	92	153	214					○	○

maximum aggregate size : 25 • • • •

Construction Cost

When replacing the conventional reinforcement with interlocking, restrictions on the size of the spirals or hoops due to the difficulty of fabrication and transportation should be taken into consideration. The relationships between bar diameter and the maximum diameter of circular hoops produced from standard bar length are shown in Figure 3. Generally, the maximum hoop diameter that can be transported is 3.0m, and hoops of more than 3.0m diameter should be constructed on site. Over 3.0m diameter hoops are to be fabricated by two semicircular bars, which increases the length of lap splice and hooks. Table 4 summarizes the quantity of steel increased for lap splicing and hooks based on JRA requirements. It is increased by approximately 10~20%.

Estimated construction costs of bridge piers based on the material quantities required for the re-design are summarized in Table 5. The cost reduction ratios in terms of weight of superstructure and pier height are plotted in Figure 4. Solid lines in the figure demonstrate the maximum superstructure weight possible at the column height under design restrictions such as reinforcement details. As a result, applying the interlocking spirals/hoops to lateral reinforcement, 10~20% cost reduction can be expected except in case 10, where the column section was enlarged due to its heavy dead load.

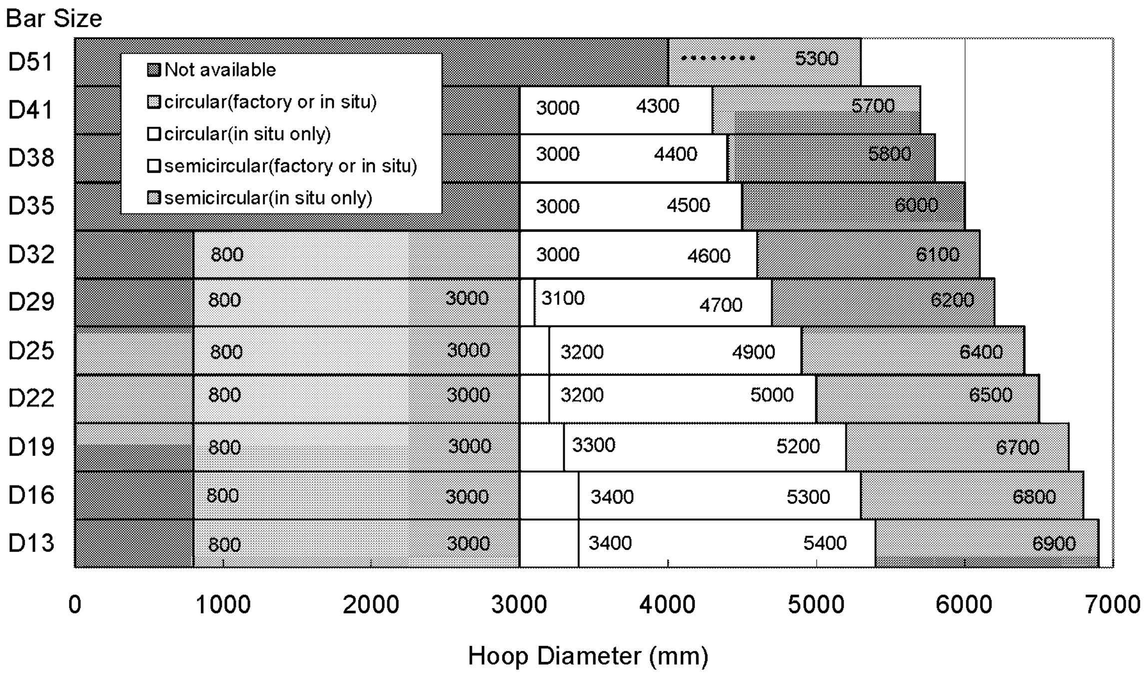
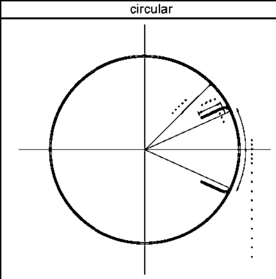
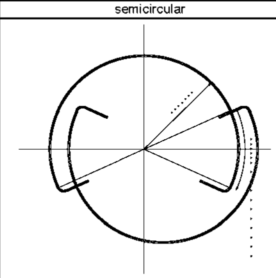


Figure 3. Available hoop diameter range

Table 4. Increase of hoop steel in lap splicing

	circular	semicircular
Shape D32 ϕ3000		
Total bar length	$L = \pi \phi + 40D + 2(12D+2\pi\, 3D/4)$ $= \pi \times 3000 + 40 \times 32$ $+ 2(12 \times 32 + 2\pi\, 3 \times 32/4)$ $= 11775$ mm	$L' = \pi \phi / 2 + 40D + 2(12D+2\pi\, 3D/4)$ $= \pi \times 3000 / 2 + 40 \times 32$ $+ 2 \times (12 \times 32 + 2\pi \times 3 \times 32/4)$ $= 7062$ mm $L = 2 \times L' = 14124$ mm
Ratio	1.000	1.199

Bar size	Hoop diameter (mm)	Total bar length ①circular (mm)	Total bar length ②semicircular (mm)	Ratio
D13	3400	11636	12592	1.082
D16	3400	11857	13032	1.099
D19	3300	11763	13158	1.119
D22	3200	11669	13284	1.138
D25	3200	11889	13726	1.155
D29	3100	11869	13998	1.179
D32	3000	11775	14124	1.199
D35	2900	11681	14252	1.220
D38	2800	11587	14378	1.241
D41	2800	11807	14818	1.255
D51	2500	11599	15344	1.323

Not available

Table 5. Material quantity and cost of target piers

Case	Category		Quantity unit	Quantity 1.Conventional	Quantity 2.Interlocking	Quantity (2-1)		Cost unit price	Cost 1.Conventional	Cost 2.Interlocking	Cost (2-1)		Remarks
1	Concrete		m³	91.667	91.667	0.000	0.0%	21,200	1,943,371	1,943,371	0	0.0%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	7.096	9.458	2.362	33.3%	112,000	794,752	1,059,296	264,544	33.3%	SD345
		Hoops	t	11.271	5.152	-6.119	-54.3%	95,700	1,078,635	493,046	-585,589	-54.3%	SD345
		Total weight	t	18.367	14.610	-3.757	-20.5%	—	1,873,387	1,552,342	-321,044	-17.1%	
	Total cost		—	—	—	—	—	—	3,817,767	3,496,313	-321,044	-8.4%	
2	Concrete		m³	110.000	66.600	-43.400	-39.5%	21,200	2,332,000	1,411,920	-920,080	-39.5%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	13.992	16.428	2.436	17.4%	112,000	1,567,104	1,839,936	272,832	17.4%	SD345
		Hoops	t	4.500	3.170	-1.330	-29.6%	95,700	430,650	303,369	-127,281	-29.6%	SD345
		Total weight	t	18.492	19.598	1.106	6.0%	—	1,997,754	2,143,305	145,551	7.3%	
	Total cost		—	—	—	—	—	—	4,329,754	3,555,225	-774,529	-17.9%	
3	Concrete		m³	202.500	173.500	-29.000	-14.3%	21,200	4,293,000	3,678,200	-614,800	-14.3%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	21.200	24.880	3.680	17.4%	112,000	2,374,400	2,786,560	412,160	17.4%	SD345
		Hoops	t	11.455	5.064	-6.391	-55.8%	95,700	1,096,175	484,646	-611,529	-55.8%	SD345
		Total weight	t	32.655	29.944	-2.711	-8.3%	—	3,470,575	3,271,206	-199,369	-5.7%	
	Total cost		—	—	—	—	—	—	7,763,575	6,949,406	-814,169	-10.5%	
4	Concrete		m³	96.540	96.540	0.000	0.0%	21,200	2,046,648	2,046,648	0	0.0%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	10.268	12.624	2.356	22.8%	112,000	1,150,016	1,413,888	263,872	22.8%	SD345
		Hoops	t	14.215	6.710	-7.505	-52.8%	95,700	1,360,376	642,147	-718,229	-52.8%	SD345
		Total weight	t	24.483	19.334	-5.149	-21.0%	—	2,510,392	2,056,035	-454,357	-18.1%	
	Total cost		—	—	—	—	—	—	4,557,040	4,102,683	-454,357	-10.0%	
5	Concrete		m³	208.355	208.355	0.000	0.0%	21,200	4,417,137	4,417,137	0	0.0%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	22.020	23.907	1.887	8.6%	112,000	2,466,240	2,677,584	211,344	8.6%	SD345
		Hoops	t	27.580	6.374	-21.206	-76.9%	95,700	2,639,647	610,233	-2,029,414	-76.9%	SD345
		Total weight	t	49.600	30.281	-19.319	-38.9%	—	5,105,887	3,287,817	-1,818,070	-35.6%	
	Total cost		—	—	—	—	—	—	9,523,024	7,704,954	-1,818,070	-19.1%	
6	Concrete		m³	192.100	160.700	-31.400	-16.3%	21,200	4,072,520	3,406,840	-665,680	-16.3%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	18.362	20.284	1.922	10.5%	112,000	2,056,544	2,271,808	215,264	10.5%	SD345
		Hoops	t	14.257	11.905	-2.352	-16.5%	95,700	1,364,395	1,139,309	-225,086	-16.5%	SD345
		Total weight	t	32.619	32.189	-0.430	-1.3%	—	3,420,939	3,411,117	-9,822	-0.3%	
	Total cost		—	—	—	—	—	—	7,493,459	6,817,957	-675,502	-9.0%	
7	Concrete		m³	630.000	483.700	-146.300	-23.2%	21,200	13,356,000	10,254,440	-3,101,560	-23.2%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	92.829	106.131	13.302	14.3%	112,000	10,396,848	11,886,672	1,489,824	14.3%	SD345
		Hoops	t	73.855	27.217	-46.638	-63.1%	95,700	7,067,924	2,604,667	-4,463,257	-63.1%	SD345
		Total weight	t	166.684	133.348	-33.336	-20.0%	—	17,464,772	14,491,339	-2,973,433	-17.0%	
	Total cost		—	—	—	—	—	—	30,820,772	24,745,779	-6,074,993	-19.7%	
8	Concrete		m³	129.600	108.500	-21.100	-16.3%	21,200	2,747,520	2,300,200	-447,320	-16.3%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	4.540	6.049	1.509	33.2%	112,000	508,480	677,488	169,008	33.2%	SD345
		Hoops	t	5.880	4.600	-1.280	-21.8%	95,700	563,033	440,337	-122,696	-21.8%	SD345
		Total weight	t	10.420	10.649	0.229	2.2%	—	1,071,513	1,117,825	46,312	4.3%	
	Total cost		—	—	—	—	—	—	3,819,033	3,418,025	-401,008	-10.5%	
9	Concrete		m³	276.260	276.260	0.000	0.0%	21,200	5,856,712	5,856,712	0	0.0%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	42.050	43.130	1.080	2.6%	112,000	4,709,600	4,830,560	120,960	2.6%	SD345
		Hoops	t	49.620	30.010	-19.610	-39.5%	95,700	4,748,634	2,871,957	-1,876,677	-39.5%	SD345
		Total weight	t	91.670	73.140	-18.530	-20.2%	—	9,458,234	7,702,517	-1,755,717	-18.6%	
	Total cost		—	—	—	—	—	—	15,314,946	13,559,229	-1,755,717	-11.5%	
10	Concrete		m³	540.540	792.560	252.020	46.6%	21,200	11,459,448	16,802,272	5,342,824	46.6%	σ_{ck}=30 N/mm²
	Steel	Rebars	t	88.256	102.307	14.051	15.9%	112,000	9,884,672	11,458,384	1,573,712	15.9%	SD345
		Hoops	t	60.900	37.354	-23.546	-38.7%	95,700	5,828,130	3,574,778	-2,253,352	-38.7%	SD345
		Total weight	t	149.156	139.661	-9.495	-6.4%	—	15,712,802	15,033,162	-679,640	-4.3%	
	Total cost		—	—	—	—	—	—	27,172,250	31,835,434	4,663,184	17.2%	

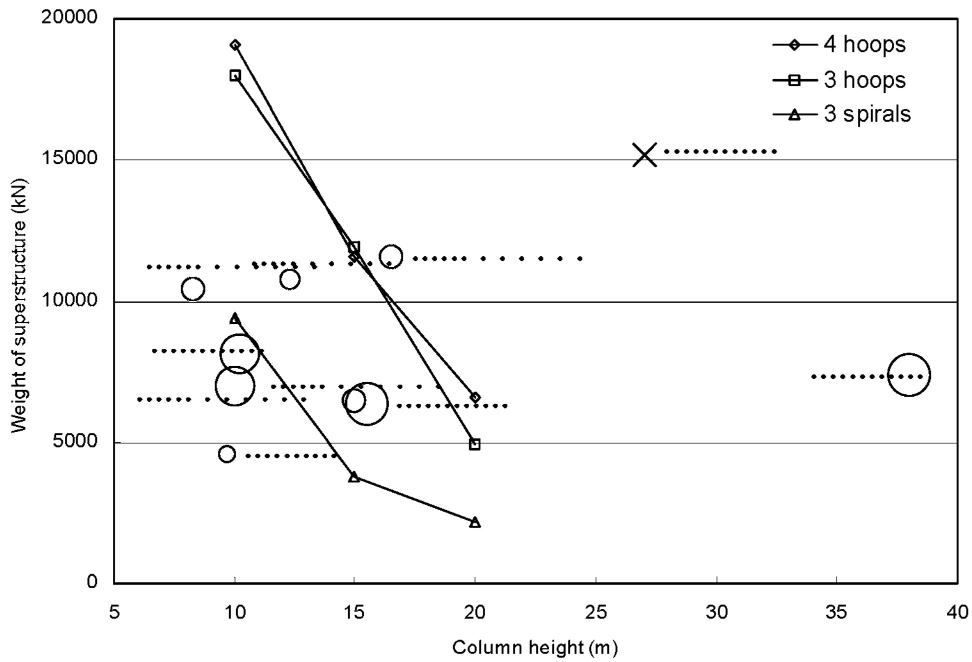


Figure 4. Cost reductions from re-design effect

Conclusions

Changing the lateral reinforcing arrangement from conventional rectangular hoops with cross ties to interlocking spiral/hoop reinforcement can lead to a 10~20% cost reduction for highway bridge piers of a variety of column heights and superstructure weights. Considering several designs, an economical application range of interlocking reinforcement is summarized in Table 6. We intend to apply interlocking spiral/hoop reinforcement to highway bridge piers where construction cost is expected to decrease compared to that of the conventional piers.

Table 6. Economical application range of interlocking reinforcement

No.	Category	Application Range
1	Structure type	Rectangular solid column section (not hollow section)
2	Weight of superstructure	4000 - 12000 kN (depend on superstructure type and span length)
3	Height of Pier	10 - 40 m
4	Aspect ratio of column cross section	1.5 - 3.25 (4 interlocking spirals/hoops maximum)
5	Available hoop diameter	3.0m maximum for spirals Over 3.0m diameter, hoops may consist of semicircular hoops
6	Possible maximum weight of superstructure	For hoop diameter of 3.0m or less, Height of Pier:10m• • • Weight of superstructure:19100kN Height of Pier:15m• • • Weight of superstructure:11900kN Height of Pier:20m• • • Weight of superstructure:6600kN
7	Support system	as designed
8	Soil condition	as designed
9	Foundation	Footing, Pile, as designed

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