UDC691.328.4:624.16

Development of New Type of Steel-Element-Concrete Composite Bridge Pier

Takeshi Katayama*1
Akira Komatsu*2
Kenji Nishiumi*3
Hisashi Hirata*1
Takashi Kuga*1

Abstract:

A new type of steel-element-concrete composite pier that had its conventional reinforcing bars replaced by steel elements or modified straight-web sheet piles was developed for use as a highway bridge pier. The straight-web sheet piles had oblong holes drilled in the web to integrate the steel elements with the concrete. The concrete bond performance, bending load carrying mechanism, and shear load carrying mechanism of the steel-element-concrete composite pier were investigated by model experiments. The steel-element-concrete composite pier was verified to have the same earthquake resistance as the conventional reinforced concrete pier. As part of a joint research project with Japan Highway Public Corporation (JHPC), steel-element-composite piers were test built to support the Joshin-etsu Expressway within 75% of the construction period for that of comparable conventional reinforced concrete piers. Based on these test construction results, construction of a steel-element-concrete composite pier was calculated for application as a bridge pier of about 60 m height. These calculations confirmed that the construction period of bridge piers would be shortened. The test construction data and calculation results are reported here.

1. Introduction

Japan Highway Public Corporation (JHPC) is planning to construct highways that pass through mountainous regions, and a second Tokyo-Nagoya and Nagoya-Kobe Expressway. The former highways will require steel-element-concrete composite piers to cross steep mountains. The latter will rest on piers for about 40% of the total length of about 200 km, and 30% of the piers will stand 40 m or more above the ground.

The increasing scarcity of workers and the aging of skilled workers make it all the more difficult to obtain necessary labor in terms of both quantity and quality. These trends are expected to accelerate further.

Against this background, development of new pier construction methods is required for building piers faster with less labor and more mechanization. In 1992, Nippon Steel started a joint research project with JHPC's Bridge Section Research Institute called "development of the method for construction of tall bridge piers with steel elements". Nippon Steel also initiated joint research with Obayashi Corp. on a method of form construction using the stiffness of steel elements.

Increasing height of reinforced concrete piers increases the amounts of structural necessary reinforcement, supports and erection bars, and the complexity of construction. The steel ele-

*1 Structurals Group
*2 Engineering Divisions Group
*3 Technical Development Bureau

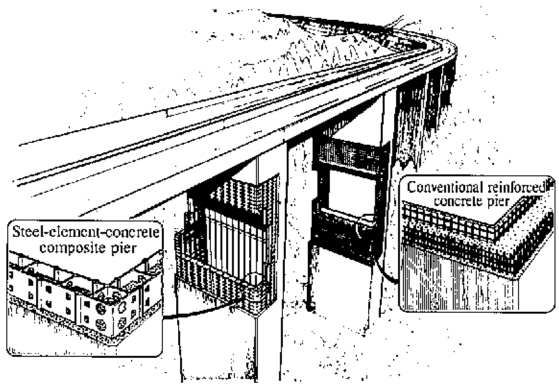


Fig. 1 Schematic illustration of steel-element-concrete composite pier

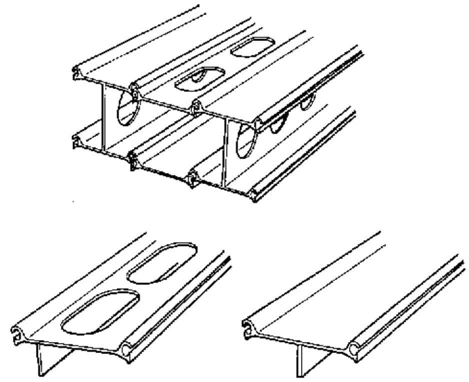


Fig. 2 Steel elements for steel-element-concrete composite pier method

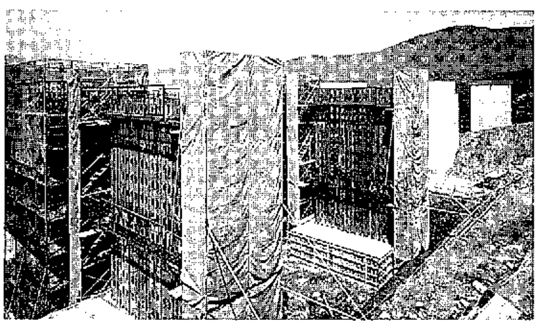


Photo 1 Steel-element-concrete composite pier under test construction at Irita Bridge

ments are substitutes for reinforcement elements in conventional reinforced concrete piers and reduce the labor required for constructing pier bodies, and for bending and assembling reinforcing bars. The dynamic characteristics, construction procedures, and test construction results of the steel-element-concrete composite piers are described here, as shown in **Fig. 1** and **Photo 1**.

2. Description of Steel-Element-Concrete Composite Pier

2.1 Description of steel element

As shown in **Fig. 2**, the steel element is a shop-assembled straight-web sheet pile with flat bars or shapes as necessary, and is provided with an interlocking joint on each side. These steel elements are transported to a pier construction site, erected horizontally and interlocked, then connected vertically by high-strength bolts.

A steel sheet pile that is easier to erect and has improved mortar filling capacity was developed as a steel element for the steel-element-concrete composite pier. The interlocking joints of the new sheet pile are provided with an interlock strength of about 200 t/m or more after mortar filling in order to improve post-yield toughness as a composite structure. Data concerning the new straight-web sheet pile designated YSP-FLW8 are given in **Table 1**.

Table 1 Cross-sectional data of straight-web steel sheet pile YSP-FLW8 (draft)

Web thickness (mm)	Cross-sectional area (cm^2)	Unit weight (kg/m)	Geometrical moment of inertia ($I \times cm^4$)	Section modulus ($Z \times cm^3$)
8	63.76	50.05	161	38

2.2 Characteristics of steel-element-concrete composite pier

The steel element is a straight-web sheet pile that has oblong holes drilled in the web. Concrete is fed through the holes into the cover, and the covering concrete and the internal concrete are joined through the holes.

The holes and the steel surfaces assure the strength of the concrete bond. The steel elements have the same function as reinforcement elements in conventional reinforced concrete piers in this respect.

The construction characteristics of the steel elements are as follows:

(1) The steel elements are entirely shop fabricated, call for no fabrication yard at the construction site, and only need temporary storage space.

(2) Since one steel element substitutes for several main reinforcing bars, the required number of members can be reduced. Since each steel element is erected by using an adjacent steel element as a guide, it can be easily positioned and rapidly erected.

(3) The steel elements also double as horizontal reinforcing bars. This means that hoop ties are not necessary, and all that is needed is the installation of welded wire fabric to prevent the concrete from falling.

(4) Since the steel elements are high in stiffness and stand on their own, they can be used for the easy erection of forms and scaffolds.

(5) The steel elements can be used as internal form for a hollow pier.

As described above, using the steel elements obviates the need for fabrication and assembly as required for reinforcing bars, and helps reduce construction labor, simplify construction and shorten the construction period.

3. Dynamic Characteristics of Steel-Element-Concrete Composite Pier

3.1 Items studied to clarify dynamic characteristics

The following items were experimentally studied to clarify the dynamic characteristics of the steel-element-concrete composite pier:

(1) Bending strength and toughness of the steel-element-concrete composite pier

(2) Bonding performance between the steel element and concrete
(3) Shear strength of the steel-element-concrete composite pier
(4) Mortar filling and tensile strength of the interlocking joints
(5) Crack dispersion performance of covering concrete
(6) Durability against drying shrinkage of concrete

The first three are introduced here as principal dynamic characteristics of the steel-element-concrete composite pier.

3.2 Bending strength and toughness

As indicated by the collapsed expressway bridge piers after the Great Hanshin Earthquake of January 17, 1995, such bridge piers must be constructed strong enough to withstand the forces of the most powerful earthquakes. Model experiments were carried out to check the toughness of the steel-element-concrete composite piers. As shown in **Fig. 3**, a horizontal load was repeatedly applied to the top of a highway bridge pier model while a vertical load equivalent to the dead load reaction force of the model was imposed on top of the model. A reinforced concrete pier with the same cross section and steel weight (same reinforcement weight as the steel element weight) as the steel-element-concrete composite pier model was similarly tested as a control specimen. To study the applicability of the steel-element-concrete composite pier compared with circular piers, circular specimens were also tested. As described later, the steel-element-concrete composite pier specimens were not provided with welded wire fabric that must be otherwise used to improve durability.

(1) Toughness (see **Figs. 3** to **5**)

The rectangular steel-element-concrete composite pier and reinforced concrete pier specimens both have approximately the same strength and behave similarly until the maximum strength is reached. After the maximum strength, the rectangular steel-element-concrete composite pier specimen shows a milder drop of load than the rectangular reinforced concrete pier specimen. The horizontal load on the steel element or reinforcement in the base of the pier yields is defined as the yield load, and the horizontal displacement of the top of the pier at that time is defined as the yield displacement. Ultimate load is defined as the point at which the horizontal load becomes equal to the yield load after it has once exceeded the yield load. The ductility factor is derived by dividing the yield displacement into the horizontal displacement at the ultimate load. The ductility factor was calculated to be 5.5 for the steel-element-concrete composite pier and 4.8 for the reinforced concrete pier.

When the load on the outermost steel in the pier yields is defined as the yield load, the ductility factor was 7.14 for the circular steel-element-concrete composite pier. In other words, the circular steel-element-concrete composite pier has excellent earthquake resistance.

(2) Axial strain

The axial strain curves of the steel-element-concrete composite pier and reinforced concrete pier are shown in **Fig. 6**. The steel-element-concrete composite pier and reinforced concrete pier

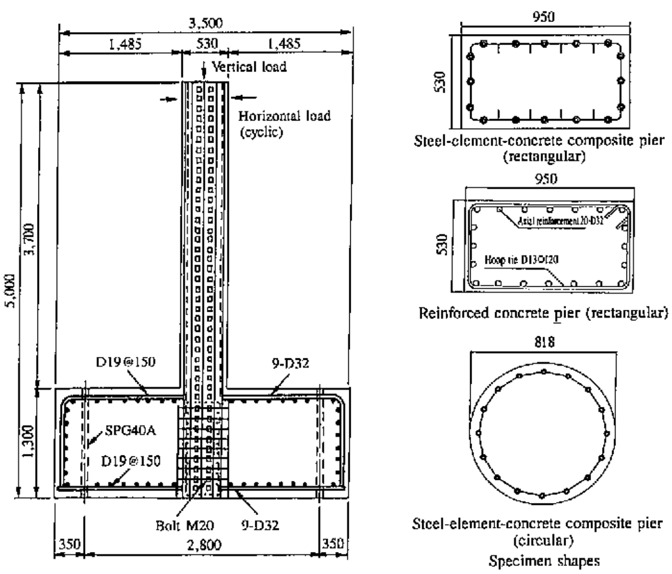


Fig. 3 Pier model experiment

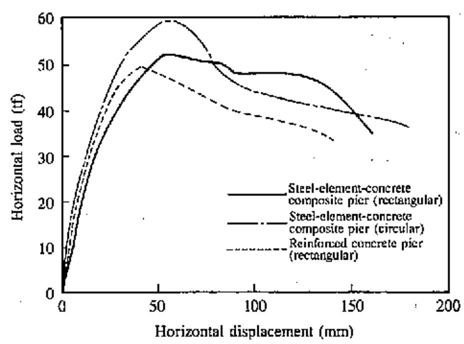
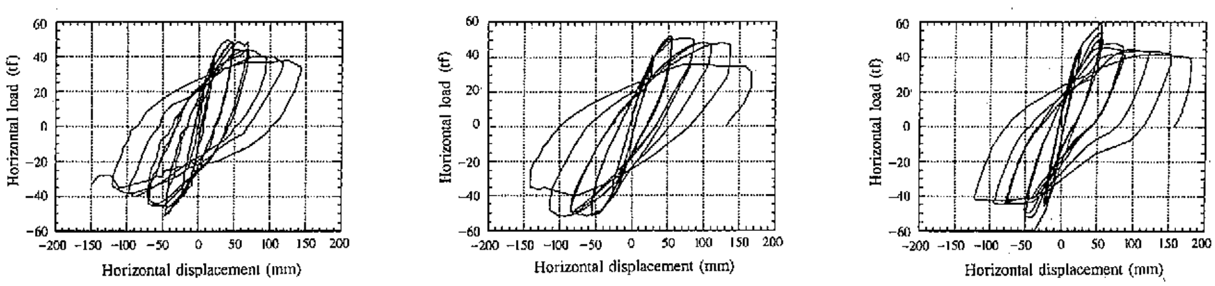


Fig. 4 Results of pier model experiment



(a) Rectangular reinforced concrete pier
(b) Rectangular steel-element-concrete composite pier
(c) Circular steel-element-concrete composite pier

Fig. 5 Horizontal load-horizontal displacement curves

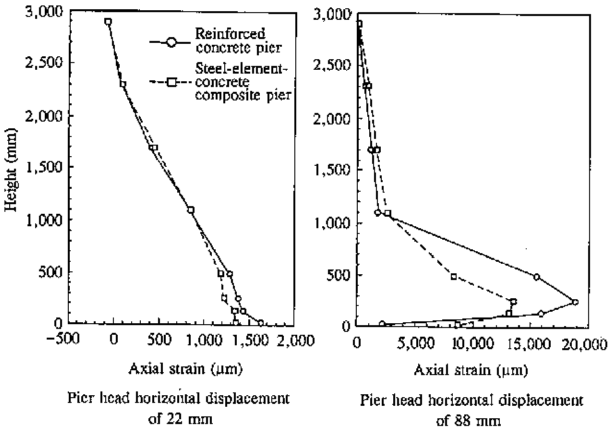


Fig. 6 Axial strain

have a similar axial strain at the 22 mm pier top horizontal displacement that corresponds to yield displacement and at the 88 mm pier top horizontal displacement where the ductility factor was 4. This means that the steel elements in the steel-element-concrete composite pier are the main reinforcement in the reinforced concrete pier.

(3) Design method

The steel-element-concrete composite pier may either be designed by the reinforced concrete method that converts the steel elements into an equivalent weight of reinforcement or by the superposed strength method. The yield load of the steel-element-concrete composite pier as evaluated by the superposed strength method was 76% of the maximum load in the model test and by the reinforced concrete method was 88% of the maximum load in the model test. The reinforced concrete method is better suited for the design of the steel-element-concrete composite pier.

3.3 Shear strength

The steel elements in the steel-element-concrete composite pier are laterally connected by means of interlocking joints. Since the interlocking joints have some construction allowance (play), the steel elements may not be continuously connected. To check the shear strength of such a structure, beam specimens were shear tested. It was confirmed that the shear strength of a pier with steel elements laterally arranged discontinuously is higher than that of a pier without any steel elements laterally arranged, but is lower than that of a pier with steel elements laterally arranged continuously. A pier with steel elements laterally arranged discontinuously was found to be incapable of being designed in the same way as reinforced concrete piers.

Regarding shear strength, the play in the interlocking joints of the steel elements must be eliminated for the steel-element-concrete composite pier to be designed in the same way as the reinforced concrete pier. For this reason, the interlocking joints are filled with mortar to transmit the tensile force. The tensile strength of the mortar-filled interlocking joints was experimentally confirmed to be higher than that of hoop ties in the reinforced concrete piers. The tension test of the mortar-filled interlocking joints is shown in **Photo 2**, and the tension test results of the mortar-filled interlocking joints are shown in **Figs. 7** and **8**.

3.4 Bond performance

The steel elements have oblong holes in the web to ensure the concrete filling of the covered side. These holes are considered to

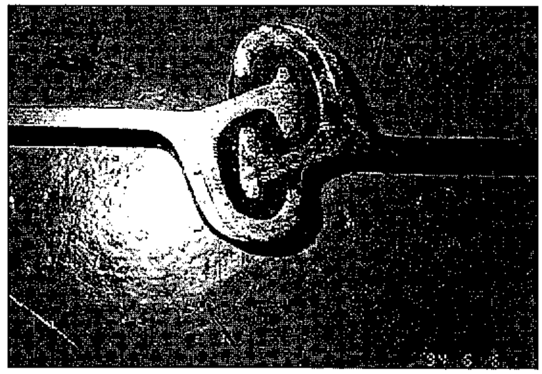


Photo 2 Interlocking joint tension test specimen

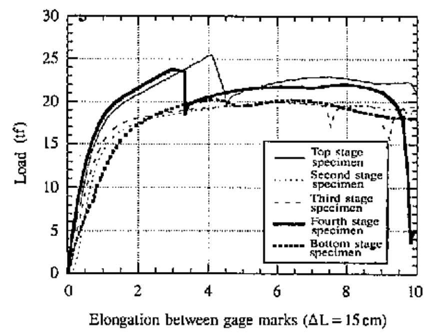


Fig. 7 Results of interlocking joint tension test

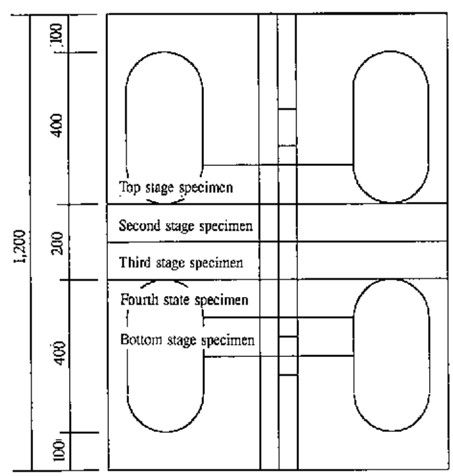


Fig. 8 Removal of specimens

work together with the steel surfaces to ensure the bonding of concrete.

The bond strength between the steel elements and concrete was tested according to the concrete-reinforcement bond strength test method (see **Figs. 9** and **10**).

The test results showed that the bond strength changes with the thickness of the cover concrete restraining the steel elements or the degree of restraint. They also show that the total bond strength is the sum of the bond strength of the holes and the bond strength of the steel surface. The bond strength was calculated by the following equation:

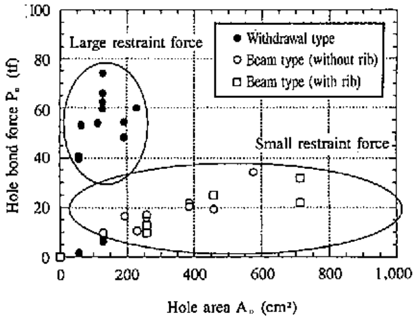


Fig. 9 Relationship between hole bond force and hole area

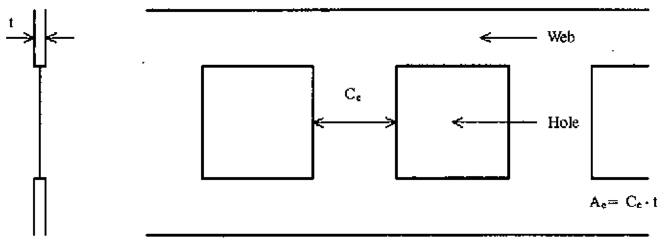


Fig. 10 Calculation of A_e

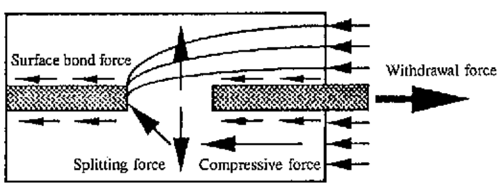


Fig. 11 Splitting failure model under bearing pressure (small restraint force)

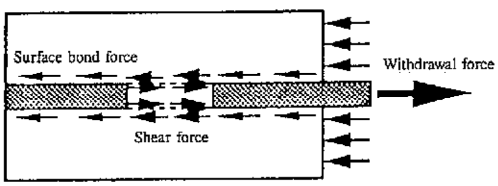


Fig. 12 Shear failure model (large restraint force)

$$\tau = \tau_s + \tau_0 \quad \cdots\cdots (1)$$

where

τ: Bond strength of steel element

τ_s: Bond strength of steel surface

$$\tau_s = 0.01F_c \cdot A_s \quad \cdots\cdots (2)$$

τ_0: Bond strength of hole

When restraint is small (flange; see **Fig. 11**),

$$\tau_0 = 0.13F_c \cdot A_0 \quad \cdots\cdots (3)$$

When restraint is large (web and rib; see **Fig. 12**)

$$\tau_0 = \mathrm{Min}(\tau_{01},\ \tau_{02}) \quad \cdots\cdots (4)$$

$$\tau_{01} = 2A_e \cdot \tau_{sa} \cdot F \quad \cdots\cdots (5)$$

$$\tau_{02} = 2.24F_c \cdot A_0 \quad \cdots\cdots (6)$$

F_c: Compressive strength of concrete

A_s: Steel surface area

A_0: Area of holes

A_e: Lateral steel surface area between holes

τ_{sa}: Allowable shear strength of steel

F: Safety factor

4. Construction Method

The primary aim of the steel-element-concrete composite pier reducing construction labor requirements and shortening the construction period. A study was conducted of the methods of erecting the steel elements and casting concrete by making use of the higher stiffness of the steel elements compared with steel reinforcement.

4.1 Erection of steel elements

The steel-element-concrete composite pier construction method is illustrated in **Fig. 13**. The lower footing reinforcement is set into position, and a stand is then installed to erect the steel elements. Since the corner elements are high in stiffness, they are first erected to assure the verticality of the pier. The intermediate elements are then sequentially erected by using the interlocking joints of adjacent elements as a guide.

After the first stage of the steel elements is erected, the steel elements and stand are bolted secure, the footing upper reinforcement is placed, and the footing concrete is cast to make the bottom end of the steel elements rigid.

The erection of corner elements, assurance of verticality, erection of intermediate elements, and bolting with the lower-stage steel elements are repeated until the specified height of the pier, or for the required number of stages, is reached.

4.2 Casting of concrete

Since the steel-element-concrete composite pier method was developed for shortening the pier construction period, the time taken for laying the concrete as well as for erecting the steel elements must be shortened. With a hollow steel-element-concrete composite pier, the internal steel elements double as form. This eliminates the need to construct cumbersome internal form otherwise required in a hollow reinforced concrete pier and therefore reduces the pier construction period.

Using a slipform sharply cuts down the construction period when the steel-element-concrete composite pier is high. As compared with reinforced concrete piers, the steel-element-concrete composite pier can easily carry the slipform reaction force at the top end due to the high stiffness of the steel elements and structural characteristics in the construction phase.

5. Test Construction

5.1 Purpose of test construction[1]

As part of the joint research with JHPC, steel-element-concrete composite piers were test built as piers for a highway bridge being constructed by JHPC. The test construction was

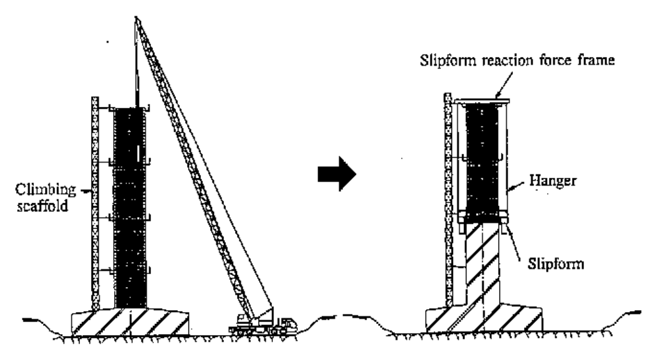


Fig. 13 Construction of steel-element-concrete composite pier

designed to see if the steel elements could be used in the construction of actual piers and if the steel-element-concrete composite piers could be built by a prestudied method.

5.2 Particulars of highway bridge selected for test construction

The particulars of the highway bridge selected for the test construction of the steel-element-concrete composite piers are given below.

Highway: Joshin-etsu Expressway
Bridge: Irita Bridge
Type of bridge: 3-span reinforced concrete continuous hollow slab + 5-span precast continuous rigid frame bridge
Selection of span length: (17.6 + 18.0 + 18.4) + (37.8 + 60.0 + 2 × 80.0 + 53.8) = 367 (m)
Piers: P1 and P2 (up line)
Pier height: 11.95 m for P1 and 13.20 m for P2

5.3 Outline of construction

The steel-element-concrete composite pier construction method was developed for tall piers. The piers P1 and P2 test constructed by the steel-element-concrete composite pier method stand 12 to 13 m tall and are relatively small structures. Piers of this height can be constructed with a single stage of steel elements. Given that the future application of the steel-element-concrete composite pier construction method will be for tall piers, piers P1 and P2 were each constructed with two stages of the steel elements, and the upper and lower steel elements were checked for ease of connection.

The construction method is shown in **Fig. 14**. In this process, leveling concrete is cast, lower reinforcing bars for the footing are placed, and then an installation stand is set into position (see **Photo 3**). A steel element with a scaffold is then erected at each corner (see **Photo 4**). The corner elements are set vertically by using chain blocks or jacks, and an intermediate scaffold is installed between the corner elements (see **Photo 5**). Using the intermediate scaffold, the intermediate steel elements are erected between the corner steel elements (see **Photo 6** and **7**). After all steel elements in the first stage are erected (see **Photo 8**), they are corrected for verticality. Upper reinforcing bars for the footing are passed through the holes in the steel elements, and concrete is cast in the footing (see **Photo 9**).

In the second stage, erection starts with the corner elements as in the first stage, and the steel elements are bolted to the counterparts in the first stage. After erection of all steel elements, crack prevention reinforcing bars are placed along the steel element surfaces (see **Photo 10**), the form is assembled, and concrete is then cast.

5.4 Labor savings

To ascertain whether labor savings would be achieved by using steel elements in the test construction, the steel-element-concrete composite piers were compared in terms of production rate with conventional reinforced concrete piers on the same up line. The two pier construction methods do not appreciably differ in first-stage assembly, but the steel-element-concrete composite pier construction method takes less construction time and requires with less labor in the second stage.

The construction period and labor engaged for the assembly and erection of steel reinforcing bars and steel elements, including the scaffolds and temporary work, are compared in **Table 2**. The construction period and labor required for the steel-element-concrete composite pier method are 74% and 94% of those for the reinforced concrete pier method, respectively.

As far as the second stage alone is concerned, the reinforced concrete piers were completed in 8 days or 47 worker-days against 5 days (63%) or 34 worker-days (72%) for the steel-element-concrete composite piers. The steel-element-concrete composite piers in this test construction project were comparatively small in height and constructed only with two stages of steel elements. The labor-saving performance of the steel-element-concrete composite pier construction method will rise with increasing pier height and expanding number of steel element stages. The piers P1 and P2 were the first highway bridge piers to be built by the steel-element-concrete composite pier method and were constructed by making necessary adjustments at the site. The test construction results indicate that further labor savings can be achieved.

6. Calculation of Applicability of Steel-Element-Concrete Composite Pier Construction Method for High Piers

The simultaneous construction of two piers, standing 62 and 52 m tall respectively, by the steel-element-concrete composite pier method was studied to ascertain the effectiveness of this construction method in shortening construction time and reducing construction costs. The design section forces of the two steel-element-concrete composite piers P1 and P2 and their comparative study results including corresponding reinforced concrete piers are given in **Tables 3** and **4**, respectively. The wind load is a predominant factor in the construction of tall piers. The sectional examination of the steel-element-concrete composite piers P1 and P2 at the maximum wind velocity of 40 m confirmed that using this method, it is possible to erect all steel elements before form assembly and concrete placement. This means that 15-m long steel elements can be preliminarily erected in four to five stages.

Box-shaped beams (about H300 in size) were installed inside the corner steel elements at vertical intervals of 15 m. The steel elements and beams are designed to withstand the wind and concrete load, and to double as slipform support columns and beams during concrete placement.

While conventional reinforced concrete piers take 120 days to complete, the steel-element-concrete composite piers can be constructed in 90 days (working day ratio of 0.7) or 25% faster. The steel-element-concrete composite pier construction schedule is outlined in **Fig. 15**.

778 tons of steel was required to construct the steel-element-concrete composite piers P1 and P2 against 815 tons for the reinforced concrete piers.

7. Conclusions

Using BH-type NS-Box shapes, steel diaphragm walls are constructed as underground retaining walls to take the place of reinforced concrete diaphragm walls. BH-type NS-Box shapes are fabricated from straight-web steel sheet piles. These straight-web sheet piles have been improved to facilitate the flow of mortar into interlocking joints and to carry the shear force of the reinforced concrete structure. This improvement has made it possible to apply the straight-web sheet piles in the construction of highway bridge piers.

In a short three-year period from 1992, the steel-element-concrete composite pier was basically tested for concrete bonding, bending and shear strength, and durability under the guidance of JHPC's Bridge Section Research Institute. In 1994, the steel-element-

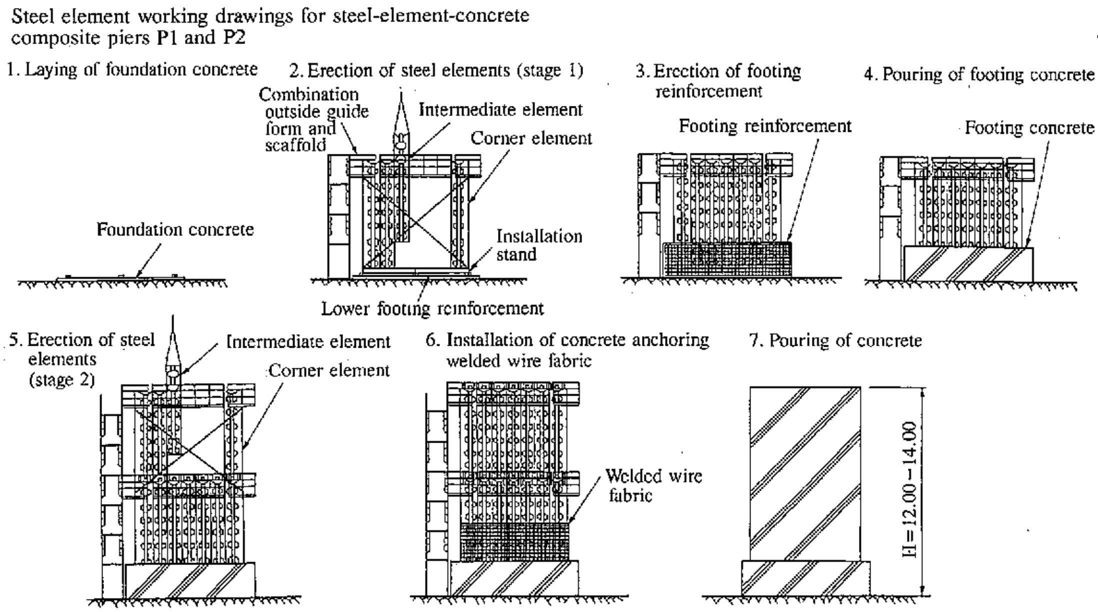


Fig. 14 Irita Bridge working drawings

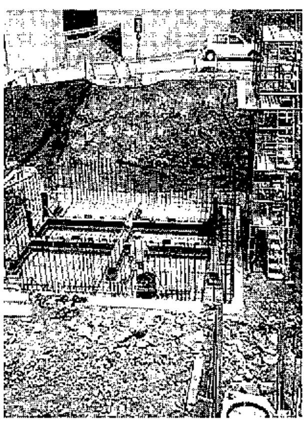


Photo 3 Setting of installation stand

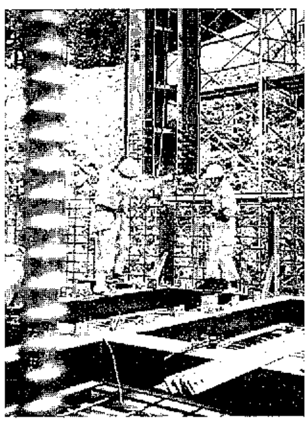


Photo 4 Erection of corner element

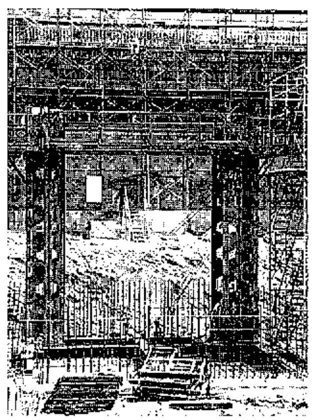


Photo 5 Corner elements installed

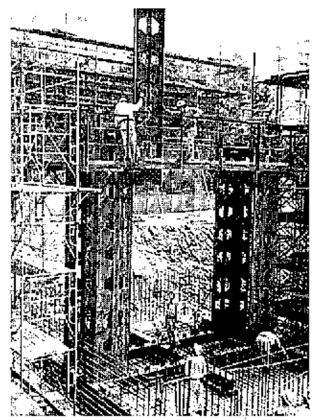


Photo 6 Erection of intermediate element

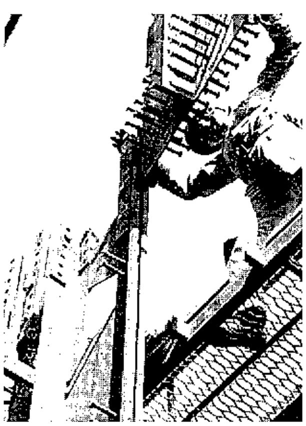


Photo 7 Erection of intermediate element (engagement of interlocking joints)

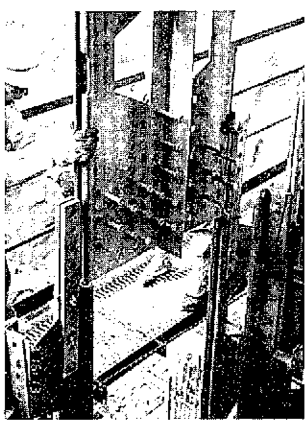


Photo 8 Erection of closing element

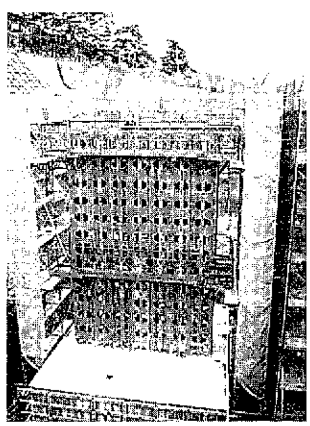


Photo 9 Erection of all steel elements completed

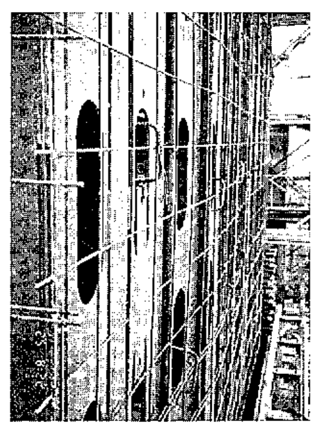


Photo 10 Installation of crack prevention reinforcements

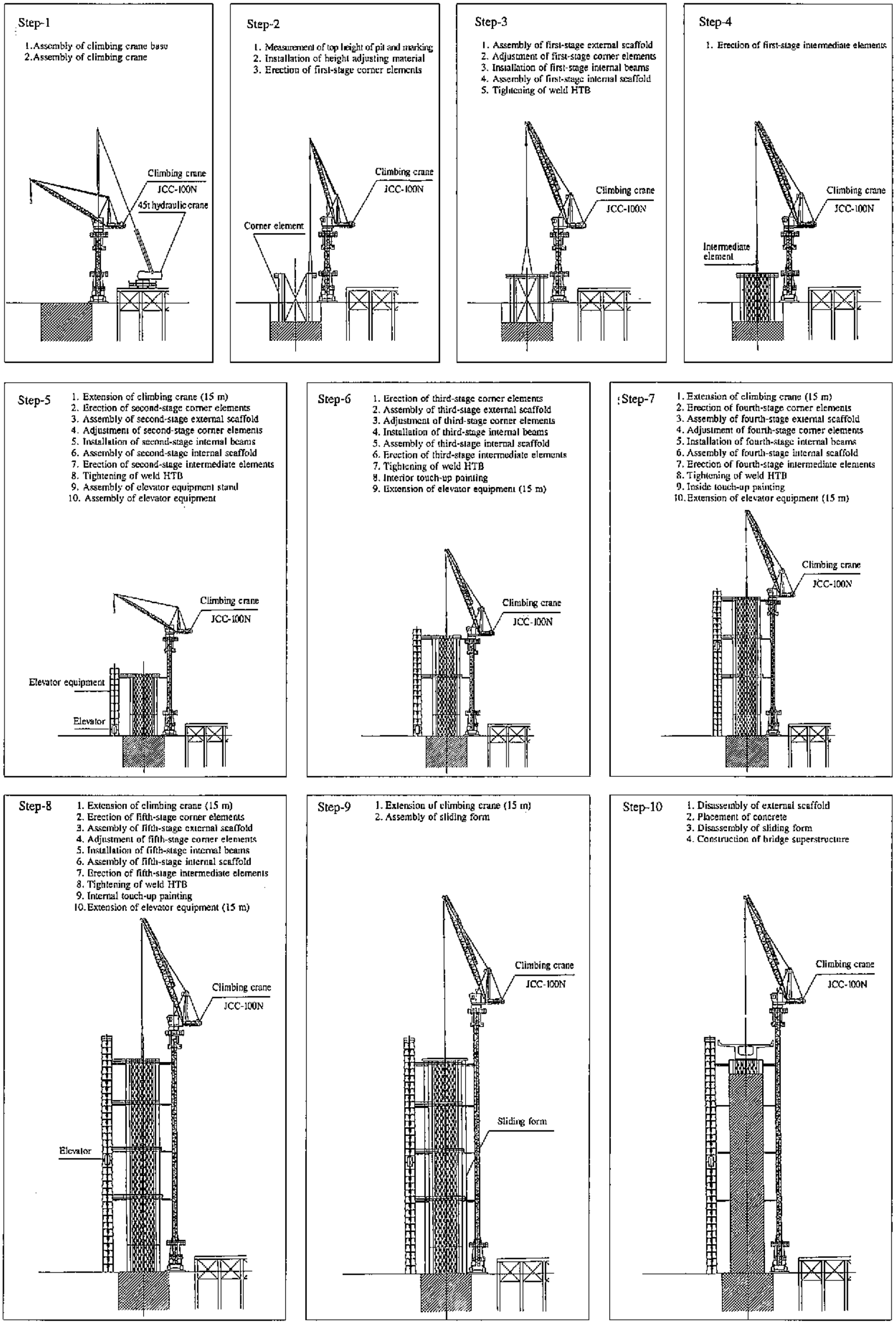


Fig. 15 Steel-element-concrete composite pier construction procedure

Table 2 Construction period reduction and labor savings by steel-element-concrete composite pier method

		Reinforced concrete piers	Steel-element-concrete composite piers
Total	Period (days)	19 (100%)	14 (74%)
	Labor (worker-days)	97 (100%)	91 (94%)
Stage 2	Period (days)	8 (100%)	5 (63%)
	Labor (worker-days)	47 (100%)	34 (72%)

Table 3 Study preconditions for steel-element-concrete composite piers

			Pier P1 (62 m high)		Pier P2 (52 m high)	
			Longitudinal direction of bridge	Transverse direction of bridge	Longitudinal direction of bridge	Transverse direction of bridge
Design sectional force	Top	Axial force (tf)	3,150	2,840	2,830	3,010
		Shear force (tf)	870	640	470	1,040
		Bending moment (tf·m)	14,670	290	14,200	1,220
	Base	Axial force (tf)	17,200	17,600	17,400	17,190
		Shear force (tf)	3,040	1,590	3,850	2,320
		Bending moment (tf·m)	43,320	65,800	64,800	96,040

Table 4 Design and schedule study results of steel-element-concrete composite piers

	Steel-element-concrete composite piers		Reinforced concrete piers	
	P1	P2	P1	P2
Quantity	390t	380t	372t Main reinforcement D22–D51	443t Main reinforcement D25–D51
Schedule	98 days	91 days	120 days	120 days

concrete composite pier method was tested at the Irita Bridge, which supports the Joshin-etsu Expressway, and its excellent construction characteristics were confirmed.

The test construction of the steel-element-concrete composite piers at the Irita Bridge involved solid piers. The bearing capacity of hollow steel-element-concrete composite piers is currently under investigation. The results of these experiments will be reported on another occasion.

Straight-web steel sheet piles now commercially available for steel elements measure 8 mm in web thickness. The thickness of stiffeners is increased to meet the sectional force of steel elements as required. Straight-web steel sheet piles for steel elements will be produced in a greater variety of section performance types to allow optimum design befitting the sectional force of specific piers.

The steel-element-concrete composite pier method can address the problems associated with shortage of skilled workers in the construction of conventional reinforced concrete piers and the aging of construction workers in general. Through application to actual highway bridge piers, the design and construction as well as economic factors will be improved. As a result, reduction in overall construction cost will be achieved by shortening the necessary construction period.

Acknowledgments

The authors would like to express their thanks to Professor Naohara Ikeda of the Yokohama National University and Chairman of the "Development of Steel-Element-Concrete Composite Highway Bridge Piers", Professor Keiichiro Sonoda of the Osaka City University, Assistant Professor Koichiro Maekawa of the University of Tokyo, Assistant Professor Shinichi Hino of Kyushu University, and the staff of JHPC for their earnest discussions at the meetings of the committee. They are also indebted to the staff of the joint venture between Sada Construction Co., Ltd. and Kitano Construction Corporation for advice in the test construction of the steel-element-concrete composite piers at the Irita Bridge.

Reference

1) Murayama, A. , Hayashi, Y. , Nishiumi, K. : Doboku Seko. 36 (1), 57 (1995)