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Technological Transition and Survey of Civil Engineering Structural Steel Materials —Trends of Technological Developments after the Great Hanshin Earthquake and the Change of Civil Engineering Material Market Needs—

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Abstract

This paper summarizes the technological transition and survey of civil engineering structural steel materials. As for the last decade, the technological aspects of civil engineering material development can be divided into two parts. The damage by the Great Hanshin Earthquake to civil structures has changed the principal design codes for bridges and port structures and so on. According to the changes of design criteria the required performance of civil engineering materials changed a lot. Consequently, several earthquake-resistant construction methods are developed. During the latter half of this decades the Japanese government decided to reduce the public construction budget. To meet the cost saving construction demand, some new civil engineering structural materials are also developed to decrease the material costs.

1. Introduction

In discussing the development of structural steel materials for civil engineering over the past 10 years or so, I consider it appropriate to begin with the changes in seismic design techniques that were made in the wake of the Great Hanshin Earthquake in 1995. And after 2000 concerning the technological developments made, in particular, it is considered appropriate to focus on those which relate to measures to reduce the expenditure on public works as part of the administrative and financial reforms.

In the years that followed the Great Hanshin Earthquake, which caused massive damage to civil structures in the area, the concepts concerning the seismic design of various types of social infrastructure have changed markedly. Those changes are reflected in the subsequent revisions of the Standard Specifications for Road Bridge Construction, the Technical Standards for Port Facilities, and the Design Standards for Railway Structures, etc. As a matter of fact, civil structures constructed in the past decade have much higher earthquake resistance than those built before the 1995 earthquake. In addition, various structural design standards have adopted critical state design or performance-based design methods in place of the conventional allowable stress-based design method, and the manner in which the client, structural designer, constructor and materials supplier involve themselves in construction projects has changed noticeably. For example, in allowable stress based design of civil structures, we—as materials suppliers—only had to guarantee the yield

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strength of the materials as the minimum requirement: we were not required to guarantee the soundness or the probability of collapse of the structure. With the introduction of the critical state design or performance-based design method, however, a number of new check items, such as ultimate strength and ductility, have been added. As a result, the quality requirements of steel materials have become more severe than ever before.

Accordingly, the scope of responsibility of the materials suppliers in terms of material quality has widened. In conventional allowable stress-based design, the yield strength is divided by the safety factor to confirm the material's stability against the anticipated seismic force, whereas in performance-based design, the yield strength and ductility factor are used to evaluate the safety factor of the structure. Thus, the scope of responsibility of materials suppliers has been clarified in that the safety factor of a given structure is determined based on the qualities of the materials used. Described below are the changes in the design systems that have been made since the Great Hanshin Earthquake, the development of new structural steel materials for civil engineering that are compatible with specific seismic design methods, and the development of various new technologies in response to the government's request for a reduction in the construction costs of civil structures.

2. Changes in Seismic Design of Road Bridge Foundations and Development of New Structural Steel Materials

The destruction of numerous bridges in the Great Hanshin Earthquake of 1995 had an immeasurable impact on bridge engineers. That incident proved that a seismic design of the 200-gal level against small to medium-scale earthquakes was insufficient to secure the safety of structures in large earthquakes. Even before the Great Hanshin Earthquake, the two-step structural design method against large-scale earthquakes was applied to architectural structures. In the revision of the Standard Specifications for Road Bridge Construction as well, it was decided to introduce the two-step structural design method. At the same time, the design procedure was changed from allowable stress-based design to performance-based design on the critical state design method. Thus, the design system was revised drastically.

Typical examples of Nippon Steel products that are designed in accordance with the Standard Specifications for Road Bridge Construction are steel materials for bridge construction and steel pipe piles/steel pipe sheet piles used for bridge substructures. Here, an outline of the revisions of the design system for bridges, mainly in terms of their substructures, is to be given, with the development of new structural steel materials for civil engineering described.

In the 1996 and 2002 revisions of the Standard Specifications for Road Bridge Construction, the main points of revision relating to steel pipe piles are as follows.

(1) Seismic intensities corresponding to large-scale earthquakes were set. (The maximum L2 load was assumed to be 2,000 gal.)
(2) A new design method based on the structural ultimate lateral strength was adopted for bridge piers and foundations. (Allowable ductility ratio of 4 was set for steel pipe pile foundations.)
(3) The limitation on horizontal displacement was eased (from 1% to 3.5% of pile diameter for poor subsoil).

Although I will omit a detailed explanation here, the above changes in design policy have made it possible to effectively reflect the high strength and excellent deformation capability of steel materials in design. As a result, the competitive edge of steel piles over concrete-based ones in design has increased and the demand for steel pipe piles and steel pipe sheet piles has expanded.

In terms of application technology also, our company has moved to develop new materials and new construction methods in response to the above revisions of the design methods. As for steel pipe piles, the Gantetsu Pile method and the NS Eco-Pile method are the two representative examples of development. The company began development of the Gantetsu Pile method, which uses a steel pipe with outer ribs and soil cement, before the Great Hanshin Earthquake. After the earthquake, the pile-bearing capacity was evaluated and the pile's horizontal resistance behavior was studied. Then, based on the results of load tests, the vertical spring constant as determined by the diameter of the soil cement was set, and a horizontal resistance design was included in the Standard specifications. Thus, we could build a design system for steel pipe-soil cement piles (**Photo 1**).

The NS Eco-Pile method, in which a blade-tipped steel pipe pile is screwed into the ground, was originally developed as an architectural foundation method. After being subjected to various load tests, this method is applied to foundations for railway bridges and road bridges. The revolving pile was included in the Pile Foundation Construction Manual (2007) that is a supplement to the Standard Specifications for Road Bridge Construction. It is expected that the NS Eco-Pile method will become much more popular in the field of road bridges in the future (**Photo 2**).

Like the caisson foundation, the steel pipe sheet pile foundation is being increasingly used as a foundation method for large bridges in Japan. The fact that no steel pipe sheet pile foundations were damaged in the Great Hanshin Earthquake is proof that this type of foundation has excellent earthquake resistance. In the design of the horizontal resistance of steel pipe sheet pile, increasing the joint strength that governs the horizontal stiffness is important. Therefore, the company has pressed ahead with its development of joint technology as well. As a recent example of construction of a large bridge foundation, the Tokyo Port Coastal Bridge can be cited. In this example, the high shear strength of the joints was ensured by using checkered steel pipe for the P-P type joint to increase the joint strength. **Photo 3** shows the Tokyo Port Coastal Bridge under construction. In the Haneda Airport Re-expansion Project that is scheduled to start in 2007, a wide joint with a high shear strength developed chiefly by

Photo 1 Gantetsu Pile construction method

Photo 2 NS-Eco-Pile construction method

Photo 3 Pile driving on barge at the site of Tokyo Port Coastal Bridge

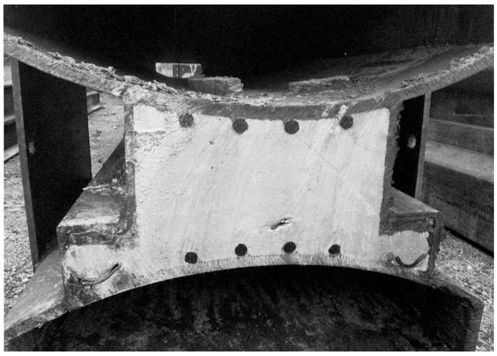

Photo 4 High Capacity and Broad type steel sheet pipe pile junction

Nippon Steel is being used for the boundary between the reclaimed land and the jacket. During an earthquake, the joints of the man-made island are subject to tremendous horizontal soil pressure, which induces a large shear force in the steel pipe sheet pile joints. In order to enable the joints to withstand that shear force, the joint structure was improved (**Photo 4**). As the improved joint structure was approved by a public organization, it was accepted for application in the Haneda Airport Re-expansion Project.

3. Changes in Seismic Design of Port Structures and Development of New Structural Steel Materials

The steel pipe piles used in pier construction and the anchor-type steel sheet piles used in revetment construction are representative structural steel materials for port structures. The Port of Kobe, which was also struck by the Great Hanshin Earthquake, stood on comparatively good subsoil. Although many of its quays and outer revetments were of concrete caisson construction and damaged, some of its steel pipe pile piers and steel sheet pile revetments suffered seismic damage. Originally, the design earthquake resistance of the port structures was not as high as that of the road bridges. Besides, liquefaction of the reclaimed ground occurred in the area. As a result, the Port of Kobe suffered immense damage. In view of the damages, the Technical Standards for Port Facilities were revised in 1998. The points of revision for seismic design of piers and sheet pile wharves in the Technical Standards for Port Facilities were as follows.

Photo 5 Pile driving by offshore pile driver at the site of Ooi container berth

(1) Setting of design for earthquake excitation taking into account the active fault and the port's terrestrial characteristics
(2) Setting of seismic forces taking into account the natural frequency of piers
(3) Introduction of a maximum lateral resistance design method for the total pier structure system
(4) Setting of design for soil pressures taking into account the stiffness of steel sheet piles
(5) Introduction of a new design check method based on nonlinear effective stress analysis in the design of anchor-type revetments.

The following two points may be cited as the major differences in technical problems in seismic design between port construction and bridge construction. Firstly, while bridges are always constructed on new routes, port structures are built and renewed repeatedly in specific coastal areas. Therefore, seismic design of port structures can be implemented based on a thorough understanding of the local seismic characteristics. Secondly, in Japan, many ports are expanded by reclamation from the shore. Thus, port structures are almost always built on poor subsoil. In the recent revision of the Port Technical Standards, the above two points were reviewed in earnest. As a result, the seismic design of port structures in Japan has reached the world's highest level. **Photo 5** shows the Oi wharf (pier supported by batter piles) at Tokyo Port that may be considered representative of the earthquake resistant quays constructed after the recent revision of the Port Technical Standards. In the seismic design of the wharf, a nonlinear dynamic analysis of the ground and pier structure was carried out in accordance with the revised Port Technical Standards.

4. Development of Civil Engineering Structural Steel Materials after the Great Hanshin Earthquake in Response to Request for Reduction in Costs of Public Works from the Ministry of Land, Infrastructure and Transport

After the Great Hanshin Earthquake, the government formulated the "Action Plan Concerning Measures to Reduce Public Works Expenditure" based on the Financial System Reform Law. The Ministry of Land, Infrastructure and Transport then asked local government and affiliated organizations to reduce the costs of public works.

In order to maintain the scale of public works projects in the face of a cut in their budget, it was indispensable to reduce the unit cost for such public works. Private companies, too, were asked to develop new technologies that should contribute to the reduction of unit costs of public works. Therefore, they began to press ahead with the development of new technologies in various business fields. The outline of the technology development Nippon Steel has undertaken to reduce costs of public works is presented below.

4.1 Development of civil engineering structural steel materials for river improvement projects

River-related projects account for a large proportion of the total budget for public works. They are carried out for various purposes, including the management of riverheads, the reinforcement of earthquake resistance of riverbanks and flood control in urban areas. Steel sheet piles have been widely used in river improvement projects, such as those for strengthening the foundations of banks and improving the earthquake resistance of revetments and banks. The conventional U-shaped steel sheet pile 400 mm in width that is used as the main structure in river improvement projects, etc. has won the strong confidence of many contractors. It has been used as both a temporarily installed structural member that is removed and reused later, and as a permanently installed structural member. For permanent structures, it was expected that employing a wider steel sheet pile would reduce the total weight of the steel material required. Therefore, Nippon Steel commercialized a 600-mm wide steel sheet pile in 1996. Then, with the aim of further reducing the construction cost and improving structural reliability and workability, the company set about developing a still wider steel sheet pile—Hat-Type Sheet Pile 900 that is 900 mm in width. These were commercialized in 2006. In the development of Hat-Type Sheet Pile 900, the joint position of the sheet pile was shifted from the neutral axis to the outer edge to improve the joint efficiency in terms of cross-section stiffness. The development of technology for production and application of the new sheet pile was completed in a short period of time. **Photo 6** shows a Hat-Type Sheet Pile 900 being driven in.

With the population concentration in urban areas in recent years, design discharge for flood have increased. Accordingly, flood discharge projects to cope with the insufficient flow capacity of urban rivers are increasing. Intended to be used in work to increase the depth of a river, the gyro-press method in which steel pipes are pressed and rotated into the riverbed has been developed. This method can efficiently be used at confined work sites where the surrounding ground conditions demand highly rigid revetments. For rivers whose channels are difficult to widen, underground facilities for storing floodwater are constructed. Flood countermeasures in urban areas are provided by river projects or sewerage projects. In many cases, the shield tunnelling method is used to construct underground river facilities in urban areas. However, since an internal pressure acts upon them during the inflow of floodwater, there are cases in which the conventional RC segment has insufficient tensile strength and cut-off performance. Because of this, the composite segment (NM segment) is being increasingly used. **Photo 7** shows the NM segments of the Kanda River Underground Reservoir in Tokyo. Development of the NM segment itself was completed in 1993. For the NM segment adopted for the said underground reservoir, however, the joint plate was simplified from the standpoint of cutting the construction cost.

Photo 6 Hat type sheet pile driving

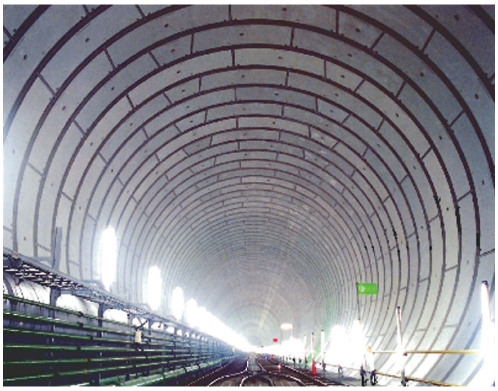

Photo 7 NM segment at the site of the Kanda River underground reservoir

4.2 Development of civil engineering structural steel materials for road projects

From the standpoint of improving the efficiency of investment in road construction, the emphasis of investment in road projects is being shifted from the development and maintenance of the nationwide network of trunk roads to the development and maintenance of loop roads aimed at improving the efficiency of traffic networks in the metropolitan areas. In the Tokyo Metropolitan area, construction of the so-called three new loop roads—Metropolitan Inter-City Expressway, Tokyo Outer Ring Road and Central Circular Route—is underway. In the Tokai area, the Tokai Circular Route is being constructed. The civil engineering structural steel materials Nippon Steel has developed for those road projects include the steel shell segment for use at diverging/converging points of urban road tunnels and the steel pipe sheet pile wall method for application to semi-underground roads in suburban areas.

In developing the steel shell segment mentioned above, the company developed a program which permits evaluating the stress that occurs in the segment taking into account the complicated steps involved in construction of shield tunnels in urban areas. The program was applied in construction of the Central Circular Shinjuku Line of the Tokyo Metropolitan Expressway. **Photo 8** shows steel shell segments of the Tomigaya Entrance tunnel on the Shinjuku Line.

As technology for the application of steel materials to semi-underground roads in suburban areas, Nippon Steel developed the steel pipe sheet pile temporary & permanent wall method and the soil

Photo 8 Large section steel segments at Tomigaya entrance tunnel of Tokyo Metropolitan Express Highway

Photo 9 Construction of Kakutabashi at Kimitsu Works

cement-steel diaphragm wall method. In the development of the steel pipe sheet pile method, the company invented a composite underground wall by dowels using perforated plate in order to secure the unity of the steel pipe and cast-in-place concrete. A design & construction manual based on a joint study of the company and the client was prepared by the Japanese Society of Steel Construction. In the development of the soil cement-steel diaphragm wall method, the Japan Institute of Construction Engineering prepared a design & construction manual.

In addition to the two methods mentioned above, the company has continued with development of new civil engineering structural steel materials for construction of urban roads. With the development of urban roads in the future, it is expected that the construction methods developed by the company will become widespread.

4.3 Development of prefabricated bridges

In Japan, new bridge construction projects have continually decreased over the past decade. However, since most of the bridges constructed during the period of rapid economic growth are almost fifty years old, it is considered that bridge renewal projects will increase in the future. Concerning small and medium-sized bridges, in particular, the need to rebuild bridges because of their obsolescence, demand for change in road plan, etc. is strong. In order to meet this need, Nippon Steel developed "*Kakutabashi*" (square steel pipe-floored bridge) (**Photo 9**) and an H-beam bridge (HBB) with rigid beam ends (**Photo 10**) for small and medium-sized bridges.

Kakutabashi is a new form of bridge developed for small bridges with a span of up to about 15 meters. First, square steel pipes are laid out side by side. Then, lateral connecting members (round steel pipes) are inserted across the array of square steel pipes and fixed with concrete at the construction site. Concerning the use of square steel pipes as bridge structural members, the fatigue characteristic of their corners when subjected to cold forming, and the effect of load dispersion of the lateral connecting members, etc. were confirmed by experiments before the square steel pipes were put into practical use.

HBBs with rigid beam-ends were developed to allow for examples with a span exceeding 25 meters, which hitherto was the limit for conventional H-beam bridges. The beam-ends are rigidly connected with bridge abutment or piers to reduce the moment that occurs at the center of the beam. For rigid connection of the beam-ends, various methods of fixing the beam-ends were studied. As a result, it was confirmed that a perforated steel dowel was superior in terms of both performance and cost. Therefore, it was put into practical use. With the use of a corrosion-resistant steel material and rolled H-beam having a height of 1,000 mm, it is expected that HBBs with rigid beam-ends will become widespread in the future.

Photo 10 Construction of HBB with rigid beam ends

5. Future Direction of Development of Civil Engineering Structural Steel Materials

The destruction inflicted on various steel structures by the Great Hanshin Earthquake in 1995 strongly shook the public's trust in steel structures and, at the same time, eroded the self-confidence of civil engineers in steel structures. However, thanks to extensive studies on seismic technology carried out subsequently, the public's trust in steel structures and the civil engineers' self-confidence have been restored. In 2000, right after the 1999 completion of the Onomichi-Imabari route—the last part of the Honshu-Shikoku Bridge Project, the government set out measures to cut the costs of public works. With the reduction in scale of public works and the intensification of competitive bids in the wake of enforcement of the revised Act Concerning Prohibition of Private Monopolies and Maintenance of Fair Trade, the total number of orders placed for public works has been decreasing continually. In addition, with the tight supply-demand situation for steel materials and the hikes in prices of raw materials and fuel, prices for steel materials are on the rise. Under these conditions, both the suppliers and users of civil engineering structural steel materials are having as hard a time as they did after the Great Hanshin Earthquake.

When it comes to selecting materials for construction of a civil structure, there is the basic principle that the least expensive materials available at the construction site should be selected. It may be said that the wide choice of materials for bridges, embankments and dams around the world reflects the diversity of civil engineering and the strong inclination toward cost minimization. How to solve the current contradictory problems—the hiking prices of steel materials and the declining budgets for civil engineering works—is a challenge for all civil engineers. It is a major issue that should be addressed while paying due attention to the effectiveness of corporate activities and the rational of social activities.

Under those conditions, the markets and technologies that civil engineers in steel structures should aim for in future are as follows. Firstly, it is considered vitally important to develop and maintain the nationwide networks of roads and ports to contribute to enhancement of the international competitiveness of the manufacturing industries, and to promote the development of technology for the application of steel materials in urban civil engineering. Secondly, it is also important to develop technology for effective use of steel materials to contribute in the formation of a safe, carefree land that has strong resistance to major earthquakes, tidal waves, and floods, etc. that may be ascribable to global warming. Thirdly, it is considered important to seek growing overseas markets for structural steel materials used in civil engineering and develop new structural steel products that are needed there.

Supplying the construction market with reliable, low-cost steel materials is a never-ending challenge to engineers in civil engineering structural materials. In setting new technical themes according to the change of the times and addressing them, the company presses ahead with speedy technological development without forgetting to make the most effective use of the advantageous characteristics of steel—its high strength, light weight, good ductility, and productivity, etc.