New Steel Technologies Essential for Social Infrastructure Development

- Steel Structure Technologies and Products Having an Impact on Society -

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In response to a wide range of requirements, NKK has developed a number of products for application in bridges, coastal civil works, steel pipes, water gates, and steel framing. This paper summarizes the trends and requirements for improvement of social capital in the field of steel structures, and reports on the primary technologies and products required to respond to the emerging needs of tomorrow.

1. Introduction

Technology associated with steel structures such as bridges, coastal structures, and water gates plays an important role in the improvement of social infrastructure such as highways, rivers, and coastal civil works. NKK has developed a number of products in the field of steel structures in response to varying requirements within society, and as such has had a unique social impact.

The current environment for public construction projects is undergoing considerable change, both in quantitative and qualitative terms, while at the same time the roles of steel structures are becoming increasingly diverse.

This paper provides an outline of NKK's products in the field of steel structures, describes the trends and requirements particularly for future social infrastructure in the area of steel structures, and reports on development of the major technologies and products designed to respond to these requirements.

2. NKK's steel structure technology and products

NKK's steel structure technology has a history of almost 80 years, and has played a central role in its steel structure products, particularly in the areas of technology for bridge design, manufacture, and construction. Early examples of NKK projects in this field are the Umaya Bridge (2550 tons, 1928) spanning the Sumida River as part the recovery project from the Kanto earthquake, and the Daishi Bridge over the Tama River (2869 tons, 1939).

In the post-war period, the Sagami Bridge (1162 tons) was the first constructed of 52kg-class steel. This project was followed by aggressive application of weather-resistant steel in bridges, and projects such as the road-rail Yoshima Bridge (part of the Seto Bridge) employing 80kg-class steel developed the company's potential as a fabricator in the area of bridge technology.

Constructions of the Metropolitan expressway and Tomei-Meishin expressway commenced in the early 1960s, and NKK completed the continuous composite girder Tomei Tamagawa Bridge over the Tama River in 1964. Participation in construction of major long span bridges commenced in the mid-1970s, beginning with the Honshu-Shikoku bridge, and including Akashi Kaikyo Bridge, the world's largest suspension bridge.

NKK introduced and established the method of transporting of bridges in large blocks on sea, and subsequent block erection, ahead of its competitors and in 1963 it constructed foundations using this method at Tennozu on Route 1 on the Metropolitan Expressway. Subsequent projects responded to requirements for bridges to span a number of straits, these including the Ogishima bridge in 1973, and the Oshima Bridge for the Japan Highway Public Corporation in 1975, as well as a number of large-block construction projects, all of which contributed to the company's considerable body of expertise in this area.

These projects covered a wide range of bridge technology, from the construction of bridge girders to the erection of bridge towers and cables for suspension bridges, and extended to steel bridge piers and steel caisson foundations.

The coupling of bridge technology with civil construction technology resulted in the first use of construction methods for underwater steel structures in piers for the Daikoku Bridge in the late 1960's. Progress in technology for underwater structures proved beneficial in caisson installation for the Honshu-Shikoku Bridge, the Tokyo Bay Bridge, and jackets and pier structures for the Kawasaki artificial island, and contributed significantly to progress in NKK's technology and expertise in the field of steel structures.

The first use of the caisson installation method was in 1979 in a 5P jacket (5400 tons) in the foundations of the Bisan-Seto Bridge. This method was subsequently used in a 3P jacket (5600 tons) on the Hitsuishijima Bridge, a 2P jacket (16000 tons) and the foundations for the tower on the mainland side of the Akashi Kaikyo Bridge, the latter being manufactured and assembled in the drydock at the Tsu works and towed by sea to the erection site.

The cable-stayed bridge as represented by the Yokohama Bay Bridge (Metropolitan Expressway Public Corporation) proliferated rapidly from the late 1960s, and there is currently a continuing strong demand for this type of bridge. NKK completed the Suehiro Bridge (2134 tons) in Tokushima Prefecture in 1973 in the initial stage of cable-stayed bridges. The company completed the Meiko Nishi Bridge for the Japan Highway Express Corporation in 1981. At the time, this bridge boasted the longest span in Japan, and introduced the use of computers for cable tensioning and control of girder shape.

The Suez Canal Bridge in Egypt (see **Photo 1**) was completed in 2001, with a central span of 404m and is of a 3-span continuous cable-stayed construction. Further work to simplify the structure while maintaining wind-stability is expected to reduce costs, and is an important theme for future development.

Photo 1 Suez Canal Bridge in Egypt (2001)

NKK's steel penstock and hydraulic gate technology has been developed over a considerable period. The company delivered a penstock to a large hydroelectric power station (Kanto Hydroelectric Power, 1928, 520 tons) on the Korean peninsula during the colonial period, and installed the Lake Sagami hydraulic gate in 1946. Building on this experience, it installed the Shinnakayama penstock in 1955, and the hydraulic gate and penstock etc. at the Shiroyama Dam in 1965.

These experiences are connected to a diverse range of hydraulic gate technology and products such as (1) radial gates for rivers, (2) peripheral technology for older dam (e.g., dam temporary closure gates), (3) technology for the ecosystem sustention through preservation of the natural environment such as fish weirs at river mouths, (4) selective water intake facilities, (5) hydraulic gates incorporating stainless cladding and stainless steel, and (6) hybrid hydraulic gate piers. The selective water intake at the Hattabara Dam in Hiroshima Prefecture (see **Photo 2**) incorporates telescopic cylinder gates of stainless steel.

The current and expected reduction in dam construction has resulted in social requirements for a diversification in hydraulic gate technology and products into environment-related peripheral technology such as gates (including control equipment), sand discharge equipment, and recycling of drifting logs.

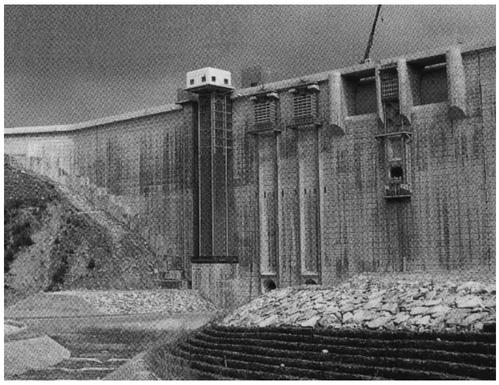


Photo 2 Hattabara Dam selective water intake facilities (1994)

Telescopic cylinder gate selects warm or clean water

Coastal structures include caissons, pontoons, and jackets. These structures are used in constructed harbors and fishing ports. NKK has developed easily constructed light-weight steel L-shaped blocks and box steel caissons appropriate for varying water depths for use in staged reclamation work. The steel caissons have been employed in approximately 20 projects, notably in construction of the Yokohama Daikoku Pier and Minami Honmoku Pier between 1975 and 1995.

Hybrid caissons (see **Fig.1**) were developed by NKK to improve the ease of construction and economy of the conventional concrete caisson. The use of boxes constructed of slabs of composite steel and reinforced concrete has reduced both weight and draft when floating. The extended footing can reduce bottom reaction force.

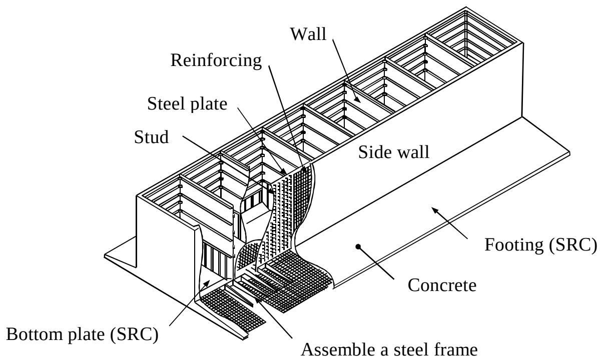


Fig.1 Hybrid caisson

In 1987, NKK was the first to construct a 13.1m deep water seawall for the Daikoku Pier, and has since constructed approximately 50 in port and harbor works, and approximately 20 in fishing ports.

Future requirements for hybrid caissons are expected to focus on increasingly stringent conditions such as greater water depths, soft ground, and rough sea conditions, improvements in structural performance such as improved seismic resistance for level-2 earthquake motion, and the addition of extra functions such as sea water exchange and wave absorbing (see **Photo 3**).

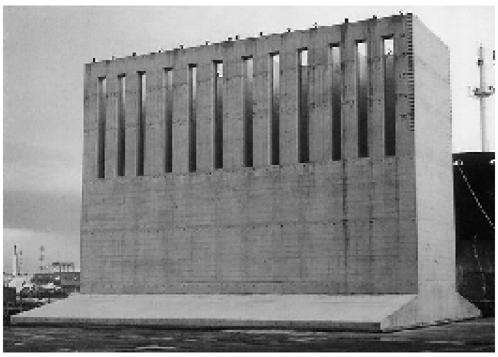


Photo 3 Seawall caisson - Ukishima (2000)
(Hybrid caisson with slit wall)

Following the delivery of the Maui A tower (11900 tons) for Shell Petroleum in 1975 for oil and gas drilling, NKK manufactured a number of large jackets (10000 - 30000 tons) until the mid-1980s. This was followed by a number of jackets for coastal applications, notably for the jacket structure for scaffolding for the Tsurumi Tsubasa Bridge on the Metropolitan Expressway (1408 tons) in 1987, and subsequently the Kawasaki artificial island (11755 tons) for the Tokyo Bay Bridge, and the Nagoya Port Central jacket structure for scaffolding for the Japan Highway Public Corporation, and recently the pier for a coal unloading facility at Hitachinaka (2560 tons).

NKK's first project in the field of immersed-tube tunnel was the manufacture of the steel casing for the Ogishima Undersea Tunnel at its Keihin Steel Plant in 1973. This was followed by projects such as the steel casings for the Kawasaki Port Undersea Tunnel, the steel casings at the ends of the Kawasaki Road Tunnel on the coastal section of the Metropolitan Expressway, and steel casing for the vertical shaft in the Minatojima Tunnel at the Port of Kobe and the Tokyo West Channel Tunnel. Investigations were conducted on seismic resistance of joints in immersed-tube tunnel and on hybrid structures during this period. Future work will involve rationalization of structures to achieve cost reductions, and development of methods of construction.

Steel construction is a traditional part of NKK's product range. Notable projects in this area included the Nagoya Railway Station (1935) as the oldest example, and two projects after World War II, B29 hangers (1946, 782 tons) and the Fuji Bank Building (1950, 1186 tons).

Examples of recent construction projects in the Tokyo Metropolitan Area for which NKK has supplied steel structural components are the new Tokyo City Offices, the Yokohama Landmark Tower, the Ebisu Garden Place, the Tokyo International Forum, and the Roppongi 6-chome redevelopment (Roppongi Hills, as shown in **Photo 4**). In addition to these major projects, NKK employs CAD/CAM-based leading-edge systems in all stages from design to production of a variety of steel structural products (e.g., steel illumination towers, and radio towers) to facilitate the supply of high-quality steel structural components.

As social infrastructure accumulates, the focus of interest shifts from new structures to existing structures. In terms of bridges, approximately half of existing bridges are of steel construction, with more than one-third of this number having been constructed more than 30 years ago, and there is therefore rapidly growing requirement for extension of the life of these structures. This trend is also apparent in water gates and other structures.

The following sections describe these typical trends and requirements in terms of NKK's technical endeavors in the areas of bridges, coastal civil works, water gates, and maintenance technology.

Photo 4 Roppongi Hills high-rise building (2002)

NKK provides 18000 tons of steel frames for Roppongi Hills

3. Low-cost cable-stayed bridges

Increasing demands for low-cost bridges in Japan have led to the adoption of the 2 main girder cable-stayed bridge. The 2 main girder cable-stayed bridge has a considerable history of use overseas, however with the unsatisfactory aerodynamic characteristics of the cross-section. Its low torsional rigidity has led to the adoption of the single box girder section to cope with the frequent attacks of typhoon in Japan. On the other hand, considerable efforts are currently underway in the investigation of aerodynamic stability[1], and a number of girder cross-sections able to withstand typhoon conditions have been proposed. Conventional aerodynamic countermeasures have primarily been a matter of altering the girder cross-section to obtain the appropriate aerodynamic characteristics. The most representative bridge designed on this basis is the Alex Fraser Bridge, incorporating an overhung deck and end plates[2].

Demands for improved economy in these structures require essential components to be effective in stabilizing the structure for the purposes of aerodynamic stability. In terms of structural mechanics as well, the need for improved stability in typhoon conditions requires measures to increase the overall torsional rigidity of the girders by such means as the use of bridge towers with high torsional rigidity.

The following describes a low-cost cable-stayed bridge without an overhung deck, and with 2 main I girder and 2-edge box girder, and presents proposals for low-cost aerodynamic countermeasures employing a maintenance passage and lifeline box. It also describes the results of investigations of structural countermeasures to increase overall torsional rigidity in order to increase the flutter onset velocity. The applicable span length for a 2 main girder cable-stayed bridge is also described in terms of flutter onset velocity.

3.1 The virtual bridge

As shown in **Fig.2**, the bridge is of a 3-span continuous cable-stayed design having a main span of 400m with a side span length of 180m (side span ratio: 0.45). The main tower is H-section in shape with double-plane cables, with floating connections between the main tower and girders. For economic reasons, the bridge construction applied 2 main I girder (section A) and 2-edge box (section B) girder without overhung deck. The 2-edge box type girder is commonly used in long-span cable-stayed bridges.

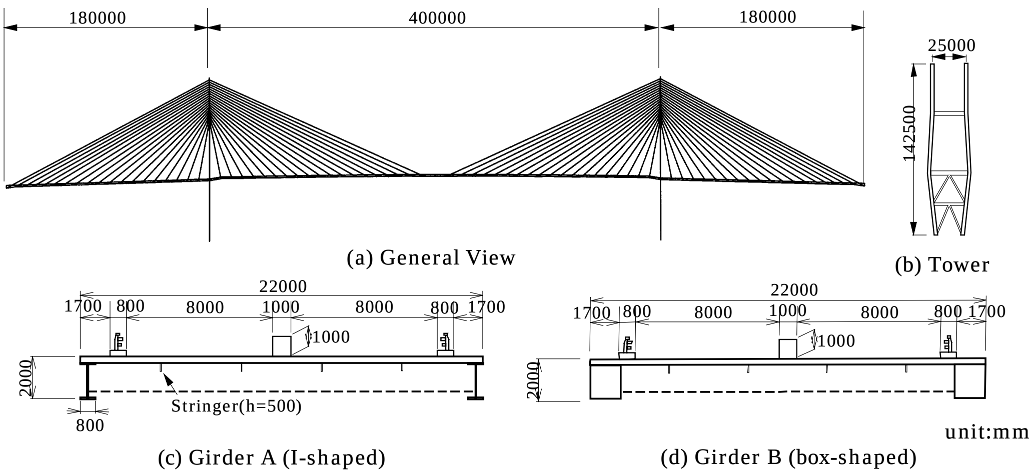


Fig.2 Investigated cable-stayed bridge

3.2 Investigation of aerodynamic countermeasures

A two-degrees of freedom spring-mounted test was conducted in NKK's 2m (width)×3m (height) working section Göttingen-type wind tunnel to investigate bending and torsional vibrations. The 1.59m model used was constructed to a scale of 1:50. Spring mounting conditions are shown in **Table 1**.

Table 1 Properties of bridge section model

Property	Prototype (assumed)	Model (Scale 1:50)
Width	22.0m	0.44m
Depth	2.0m	0.04m
Mass	25.23t/m	16.05kg/Model
Inertia	1548t・m^2/m	0.394kgm^2/Model
Damping (δ)	−	0.020
Bending freq.	0.27Hz	2.10Hz
Torsional freq.	0.54Hz	4.20Hz

These conditions assume a cable-stayed bridge with a center span length of about 400m. Each section was tested in a uniform flow at angles of attack of 0° and ±3°. Proposed aerodynamic countermeasures are shown in **Fig.3**. These measures comprise the simulation of the essential lifeline box with rectangular members to form a corner cut-off effect. These members are fitted on the inside of the main girder for the 2 main I girder, and on the top and bottom faces of the girder for the 2-edge box girder, the parameters Pa (protruded depth from I girder) and XU and XL (distances from ends of box girder) being varied as appropriate.

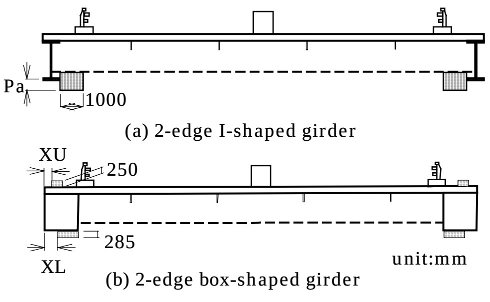


Fig.3 New countermeasures

Testing revealed the following.

(1) Aerodynamic countermeasures employing rectangular members for the maintenance passage and public lifeline box project from the 2 main I girder, are intended to produce a corner cut-off effect, can maintain the flutter onset velocity equal to or greater than that of the original section with the appropriate protruded depth, and reduce the amplitude of vortex-induced vibration. On the other hand, care is required since the appropriate protruded depth for the girder section shape varies.

(2) The section of the 2-edge box girder tested exhibited better aerodynamic characteristics than the 2 main I girder. When a corner cut-off is fitted to the bottom of the edge box girder the flutter onset velocity is reduced at positive angles of attack, however when a corner cut-off of appropriate size is fitted to the top and bottom of the girder, the flutter onset velocity is improved by approximately 15%. This measure is considered effective in increasing span length of cable-stayed bridges with edge box girder sections.

3.3 Investigation of measures employing structural mechanics

As measures employing structural mechanics to increase overall rigidity are designed to increase the flutter onset velocity, an evaluation was conducted using eigenvalue and two-dimensional flutter analyses of the entire bridge system. The primary structural properties are shown in **Table 2**. The analyzed cases included additional installation of a middle pier in the side span, addition of horizontal members to the top of each main tower, and a system for connecting the top of the main tower by cable (i.e., the tower cable system). An outline of each measure is shown in **Fig.4**. The rigidity of the horizontal member at the upper part of the tower was assumed to be the same as for the intermediate horizontal member at the top of the main tower, and the fundamental case for cross-sectional area of the tower cable system was that it was the same as for the primary cable (0.013m^2). The non-steady aerodynamic coefficient (0° angle of attack) of section A investigated in the previous section was employed to estimate the aerodynamics of the girder by the two-dimensional flutter analysis.

Table 2 Properties of analytical model

Girder	Outline	Shape	2-edge I-shaped girder
		Width	22m
	Mass	Mass	23t/m
		Moment of Inetia	2400t・m^2
	Stiffness	Area	1.05m^2
		Vertical	0.8m^4
		Horizontal	160m^4
		Bending-Torsional	85m^6
Tower	Stiffness	Out-Plane	11～20m^4
		In-Plane	6～8m^4
		Torsional	15～21m^4
	Horizontal Member	Out-Plane	6m^4(U),11m^4(L)*1)
		In-Plane	5m^4(U),7m^4(L)
		Torsional	8m^4(U),15m^4(L)

(Remarks) *1) U: Upper Member L:Lower Member

Investigation by above measures revealed that the addition of horizontal members to the top of the main tower (increasing only the torsional rigidity of the girder) was found to have the greatest effect in that flutter onset velocity was increased by 16%.

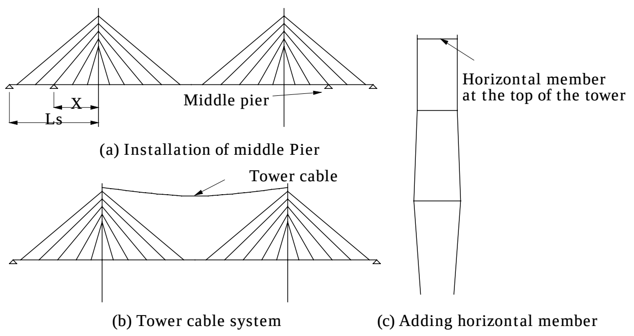


Fig.4 Concept of structural countermeasures

3.4 Investigation of appropriate span length

The appropriate span length, and the extent of the benefits to be obtained from the countermeasures proposed here, were investigated for the cases in which 2 main I girders without overhang, and 2-edge box girders, were used. Preliminary design and eigenvalue analysis were conducted for central spans of between 200 and 600m (side span ratio : 0.45), and the 1st mode frequency for bending and torsion calculated, after which the two dimensional flutter analysis was conducted using the non-steady aerodynamic coefficients of the basic cross-sections (girders A and B) in this investigation, and the modified cross-sections. The modified cross-sections comprise a 2 main I girder section A with Pa = 80cm, and a 2-edge box girder section B with XU = 30cm and XL = 45cm. The results of the investigation are shown in **Fig.5**. Cases analyzed comprised angles of attack of 0º and ±3º, however **Fig.5** shows only the minimum wind velocity. This analysis revealed the following.

In terms of flutter characteristics of the 2 main I girder section without overhang, analysis showed that countermeasures are required when the central span exceeds 300m. If the low-cost aerodynamic countermeasures proposed in this paper are implemented a length of the central span of up to 400m is possible. If the proposed countermeasures are implemented with the 2-edge box girder section, a length of the central span of beyond 600m is possible.

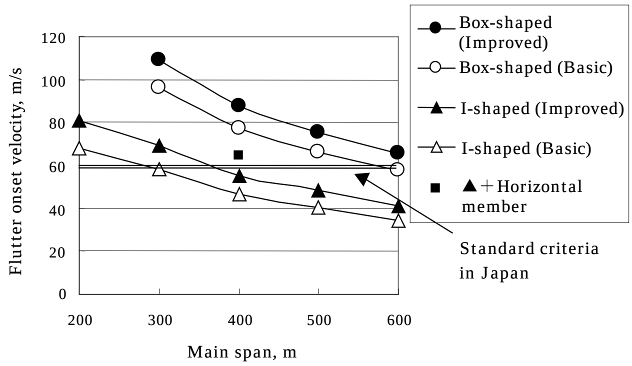


Fig.5 Relationship between main span length and flutter xonset wind velocity

4. Hybrid caissons

Hybrid caissons have been used in quay walls, seawalls, and breakwaters. However in addition to the requirements as described in Section **2**, a reduction in construction costs has also become increasingly essential. In this section 'Application of hybrid caissons in high seismic resistant quays', 'Hybrid caissons seawater with exchange functions', and 'Sloping top caissons with slit walls' are presented as examples of development in which these problems were faced.

4.1 Application of hybrid caissons in highly seismic resistant quay walls[3)]

4.1.1 Experiments on virtual high seismic resistant quays

Hybrid caisson type quays are a variant of a gravity type quay wall, and are designed on the basis of stability calculations (e.g., sliding and overturning), which assume the wall body can be taken as the portion between the face line of quay wall and the vertical plane passing through the rear toe of the caisson (edge of the landside footing). In practice, no clear understanding of the effective weight of the backfill rubble above the landside footing during level-2 earthquake conditions had been available. An experiment was therefore conducted in which the wall width, weight, and position of center of gravity were the same for a hybrid caisson and a conventional caisson, and the effects of seismic resistance on side backfill rubble above landside footing was compared. Cross-sections of test models are shown in **Fig.6**.

The Hachinohe wave from the 1968 Tokachioki earthquake was employed as the input seismic motion, and the peak value of the shake table accelerations was reached to 170 Gal, 340 Gal and 510 Gal in each step.

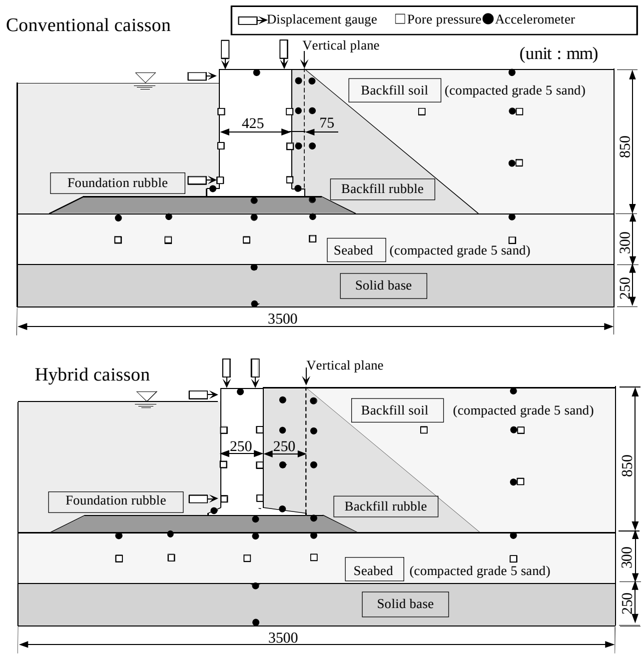


Fig.6 Cross-sections of test models

From the conditions of the ground around the hybrid caisson model before and after application of the seismic motion, it was apparent that the vertical plane remained vertical following application of the seismic motion, and the backfill rubble above the landside footing moved together with the caisson. Horizontal residual displacement of the top of the caisson is shown in **Fig.7**. The horizontal axis represents the maximum acceleration measured at the surface of the backfill soil converted to an equivalent seismic coefficient Ke as used by Noda and Uwabe (equation 1) for port and harbors structures, with the threshold seismic coefficient Kc at the sliding limit of the model subtracted to produce a non-dimensional quantity.

$$Ke=\cdot\ /g(\cdot\ \ \cdot\ \ 200Gal),\ Ke=1/3(\cdot\ /g)^{1/3}(\cdot\ >200Gal) \quad .... (1)$$

where;

・ : Peak ground acceleration (Gal)

g : Acceleration of gravity (Gal)

Seismic motion exceeding the threshold seismic coefficient acts at Ke/Kc>1. In every case in which seismic motion was applied, the hybrid caisson returned a value for horizontal residual displacement at the top of the caisson approximately 10% lower than that from the conventional caisson. It is possible that this is a result of absorption of the vibrational energy by the crushed stones in the backfill rubble.

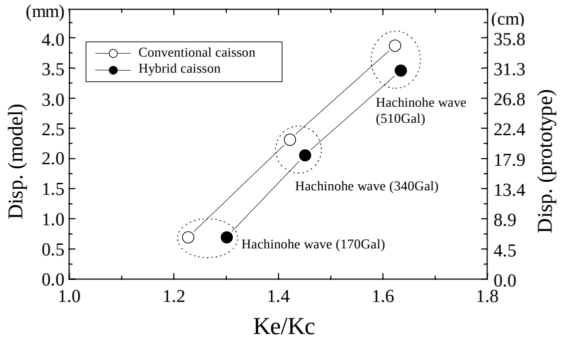


Fig.7 Residual displacement at the top of the caisson

4.1.2 Application to Shin-Okitsu quay wall (port of Shimizu)

The Shin-Okitsu quay wall at the Port of Shimizu in Shizuoka Prefecture has been under construction since 1999 as a public wharf and high seismic resistant facility able to handle overseas container vessels. The hybrid caisson structure shown in **Fig.8** was adopted for the quay wall.

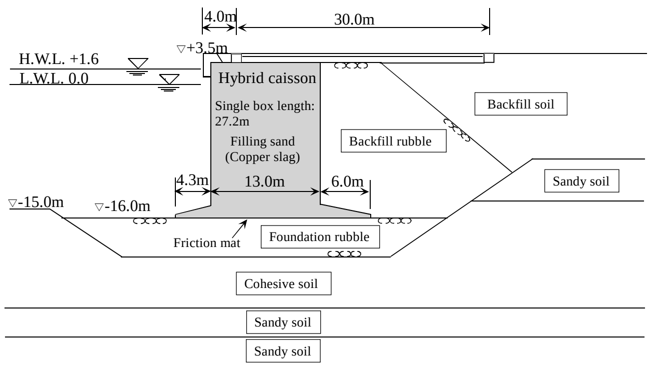


Fig.8 Cross-section of Shin-Okitsu quay wall

4.2 Hybrid caissons with seawater exchange functions[4)]

4.2.1 Seawater exchange mechanism

The seawater exchange mechanism is shown in diaphragmatic form in **Fig.9**. In the condition of forward wave, the mass of water rides over the submerged vertical plate, the water level rises, and seawater enters the harbor. In the condition of backward wave the submerged vertical plate obstructs the lowering of the water level between itself and the rear wall, thus preventing a flow of water and ensuring that the flow of water is always in the same direction.

4.2.2 Application at Misaki fishing port

The area inside the harbor is planned for use as a fish preserve, so that part of the southern breakwater was constructed with a seawater exchange function to produce a hybrid caisson breakwater with a double-slit wall as shown in **Fig.10**. The southern breakwater was designed for ex-

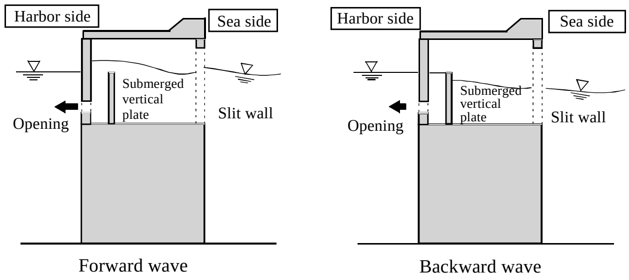


Fig.9　Flow pattern with seawater exchange

tremely severe conditions, with a depth of between 10 and 20m, and a wave height of 11.9m. The double-slit wall structure was incorporated for wave dissipation between the long and short periods, and the submerged vertical plate is of two heights to accommodate the effects of changes in the tide level, and thus ensure sufficient seawater exchange during the period of low wave height in summer. Channels are 1200mm in diameter, and spaced at 4m intervals.

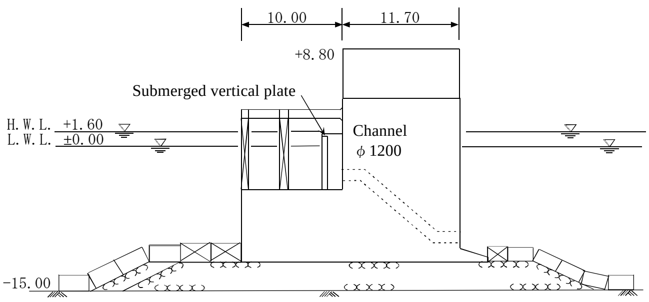


Fig.10　Cross-section of breakwater with seawater exchange function at Misaki fishing port

4.3　Sloping top caisson with a slit wall[5)]

4.3.1　Outline of structure

As shown in **Fig.11**, the sloping top caisson with a slit wall is the conventional wave-absorbing caisson with the seaward top corner inclined, the vertical component of the wave forces acting to stabilize the caisson and thus provide superior structural resistance against wave action.

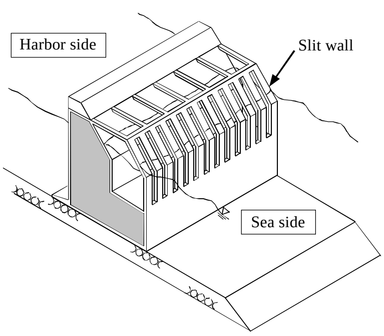


Fig.11　Sloping top caisson with a slit wall

4.3.2　Hydraulic model test

The model shown in **Fig.12** (1:60 scale, 30% slit opening ratio) was employed in testing of a breakwater constructed in 15m-deep water.

Fig.13 shows a comparison of the critical weight for sliding of the vertical caisson with a slit wall and the sloping top caisson with a slit wall under various wave conditions (wave height and period). This comparison was obtained using the design wave formula for the sloping top caisson with a slit wall as derived from a series of experiments. Within the comparatively small range of wave height there is almost no difference between the vertical caisson with a slit wall and the sloping top caisson with a slit wall, however as wave height increases this difference becomes more noticeable. Under rough sea conditions, for example at a wave height of 10m, the required weight is reduced by approximately 40% in comparison with the vertical caisson with a slit wall. This indicates that the structure of the sloping top caisson with a slit wall provides economic benefits under rough sea conditions.

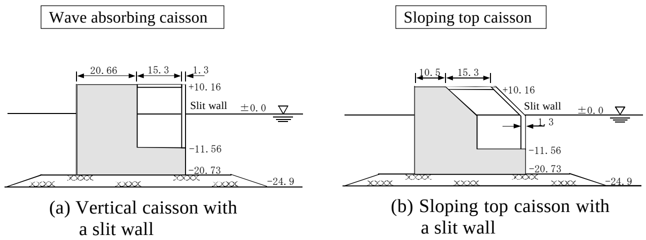


Fig.12　Cross-sections of test models

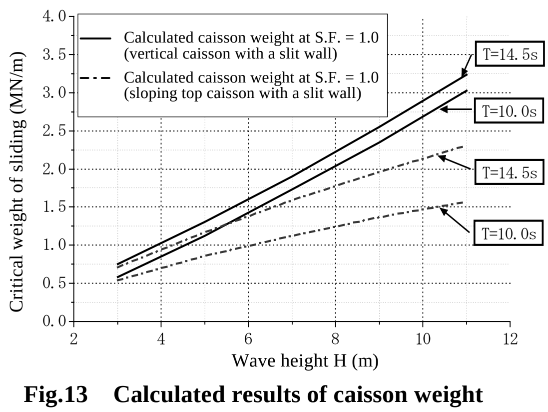


Fig.13　Calculated results of caisson weight

(water depth h = 15m, wave period T = 10.0sec, 14.5sec.)

5.　Preventing water intrusion in subways

Water intrusion prevention facilities for subways are installed in underground facilities and tunnel ventilation outlets to prevent entry of rainwater and others. Development of this facility is proceeding in light of the recent water intrusion damage resulting from heavy rains in the metropolitan area.

As subway tunnels frequently pass under main roads the ventilation exits are installed in footpaths or in the median strip. This prevents raising the height of the ventilation exit, so that the exit is frequently at ground level and thus readily subject to ingress of rainwater.

Ventilation exits are normally installed at intervals of between 100 and 500m, with between 2 and 15 units of the equipment fitted to each ventilation outlet. Flap-type equipment (as shown in **Fig.14**) has conventionally been fitted to ventilation exits. The recently developed radial gate equipment for preventing water intrusion (as shown in **Fig.15**) resolves the problems associated with the conventional flap-type, and has the following characteristics.

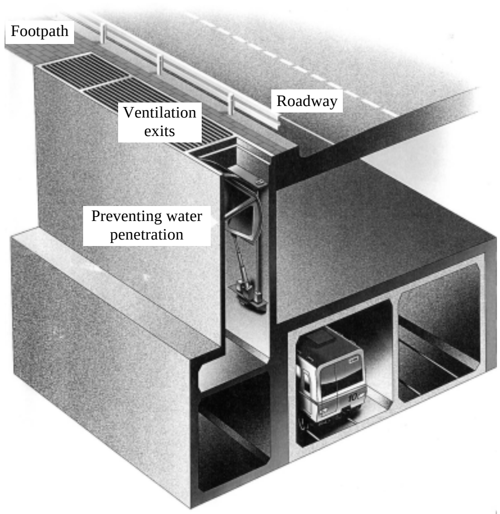


Fig.14 Equipment to prevent water intrusion in subways

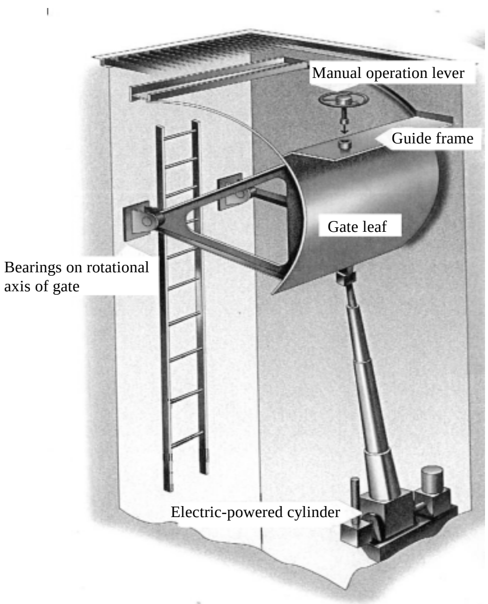


Fig.15 Radial gate type facility to prevent water intrusion in subways

(1) Reduced force and time required for opening/closing

The entire water pressure load on the radial gate acts through the rotational axis. As the water pressure acts directly on the gate, the force required for operation is reduced in comparison with the conventional flap-type. This reduction in force required for operation allows a large number of gates to be operated simultaneously for the same power consumption, and a reduction in a time required for opening and closing. Application in facilities operated by the Teito Rapid Transit Authority showed that while two conventional flap-type units could be operated simultaneously, six radial gate units could be operated simultaneously and in only 1/3 of the time.

(2) Improved reliability

This design simplifies opening/closing mechanism of the gate leaf, while incorporation of moving components (e.g., gears) and gate position sensors in the electric-powered cylinder prevents ingress of foreign matter into the machinery, while preventing incorrect operation of the sensors. Use of an overload limiter detects overload in the unlikely event of foreign matter becoming caught in the gate, and allows automatic stop and indicates fault display.

(3) Safe operation

Manual operation of the gate is possible from the side if it cannot be operated electrically, however an interlocking mechanism is fitted to improve safety with manual operation and during inspection when electrical operation must be disabled. Indicator lamps are also fitted to allow the operator to verify that the gate is fully closed during manual operation.

The radial gate is frequently used in dam outlet facilities, and NKK also has experience this area, however the fact that its use in this application is subject to different conditions, and its small size and use in large numbers, led to manufacture of a test sample of the same scale to investigate (a) the adequacy of its structure and functions (water-tightness, ease of operation, and verification of closure), (b) its compatibility with operational control equipment (compatibility with electrical equipment and verification of functions), and (c) manufacture (structure, method of manufacture, materials used, and method of painting) and thus establish functions and technology appropriate for the conditions of use. 32 units of this model of radial gate were ordered by the Teito Rapid Transit Authority in 2001, and delivered in the same year. See **Table 3** for basic design criteria.

Table 3 Basic design criteria

Model	Radial gate
Gate size	850mm×900mm
Design head	Operating head + 2m water head
Operating head	Water head from gate leaf to road surface
Open/close	Electric-powered cylinder
Open/close time	20 sec.
Control system	Local control, remote control(station), automatic and manual operation

6. Maintenance technology

As we greet the 21st century, society faces an era of critical change, in which financial reserves for investment and development of new social infrastructure are reducing. The question of how to maintain and to make effective use of existing social infrastructure are topics of great importance. The 21st century is called as "the era for maintenance technology". In terms of bridges, for example, the number of bridges older than 50 years will increase dramatically in the future, and it is expected that maintenance costs will exceed investment in new construction. NKK is aggressively involved in technical development to respond the requirements of those needs. The following introduces some typical technology of the inspection, diagnosis, and monitoring.

6.1 Checking, inspection, and evaluation

Optimum maintenance requires precise understanding about the various kind of damage that occur. The NKK technology available for this purpose is shown in **Table 4**.

As an example of this checking and inspection technology, the following describes 'Non-destructive inspection using infrared thermography'[6]. This technology is applicable to non-destructive inspection of welded components (e.g., anchor bars, faceplates) in steel expansion joints in road bridges without digging up the road surface. As shown in **Fig.16**, this method consists of a localized heating of the faceplate in an expansion joint for a short period of time and an analysis of the resulting thermal diffusion to evaluate the integrity of components. **Fig.17** shows a comparison of thermal diffusion analysis results of components between with and without damage.

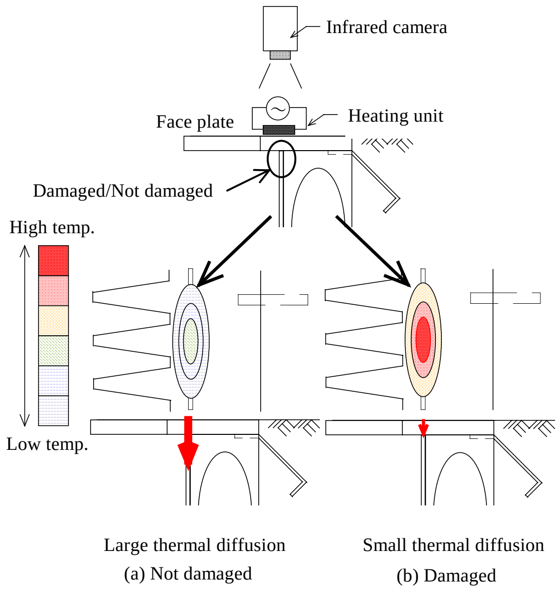
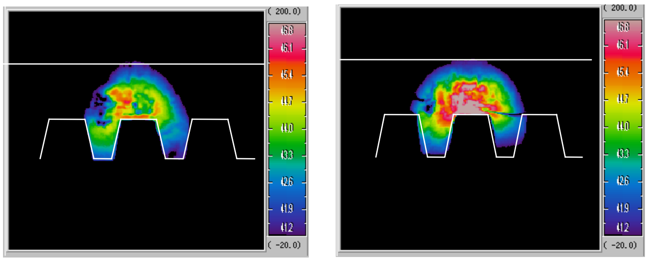


Fig.16 Defect detection using infrared radiation thermometer

Table 4 Technology for inspection, estimation, repair, reinforcement, and replacement of steel structures

Maintenance phase	Applicable technology	Outline
Checking, inspection, and evaluation	Non-destructive inspection using infrared thermography (**Fig.16, 17**)	Investigation of damage and reduced thickness using an infrared camera
	Ultrasonic phased array technique	Highly functional flaw detection using phase control of ultrasonic
	Measurement of deterioration of paint film	Measurement of the extent of deterioration of paint film using AC impedance measurement
	Acoustic diagnosis	Crack and void inspection using acoustic analysis of acoustic hammering test results
	Crack measurement	Measurement of length of cracks in concrete using image processing techniques
	Laser Doppler vibration measurement	Remote measurement and analysis of vibration of beams and materials
	Environmental measurement	Quantitative measurement of water content, atmospheric salt particles, SOx, and NOx etc.
Monitoring and diagnosis	Bridge health record database	Integrated management of data (e.g., diagnosis results, construction records, and repair history) based on checking and inspection.
	Magnetic stress measurement using magnetic anisotropy sensor (**Fig.18, 19**)	Non-contact, non-destructive stress measurement (absolute stress measurement technology)
	Fatigue damage measurement (**Fig.20**)	Fatigue damage measurement using a fatigue sensor
	Simplified stress frequency measurement	Simplified autonomous equipment for measurement of dynamic stress
	Evaluation of remaining fatigue life	Precise estimation of remaining fatigue life based on inspection results and reliability theory
	Evaluation of remaining paint life	Precise estimation of remaining life of paint film functions based on inspection results and reliability theory

A low-cost and accurate inspection can be achieved by applying this technology under conditions of minimal highway traffic control. It has been highly evaluated by the authority in charge and is included in road management inspection manuals.



(a) Not damaged (b) Damaged

Fig.17 Thermograph of faceplate

6.2 Monitoring and diagnosis

The most important capability for the predictive maintenance is to measure, monitor and diagnose damages, and it is strongly required rather than the treatment after the damage.

The following introduces monitoring sensors of applied stress and fatigue damage, and diagnosis technology, which are a current subject of much interest.

Fig.18 shows the principle of the magnetic anisotropy sensor[7]. It measures the change of anisotropy of magnetic permeability generated by an applied stress condition (**Fig.19**). A magnetic anisotropy sensor works only by putting it on an object to be measured whose surface may be normally painted or heavy duty anti-corrosion coated up to a few millimeters in thickness, therefore, a completely non-destructive measurement is achieved. It does not require special preparation and pre-processing, and is an excellent technology for simple and immediate on-site stress measurement. As the stresses are measured in the form of absolute values, this method is effective for the evaluation of dead-load stress and residual stress.

The fatigue sensors shown in **Fig.20** are applicable to various kinds of stress levels. Each sensor is placed on a structure for a certain period of time (e.g., one month, or one year), which generates the propagation of the sharp artificial crack in the sensor. The extent of fatigue damage to a structure (i.e., the rate of fatigue damage) is estimated by measuring the crack propagation length. It is necessary to visit the site both to put the sensor and to measure the crack propagation. Automatic data acquisition system can be also applicable. Basically, the fatigue sensors work themselves without the need for a power supply.

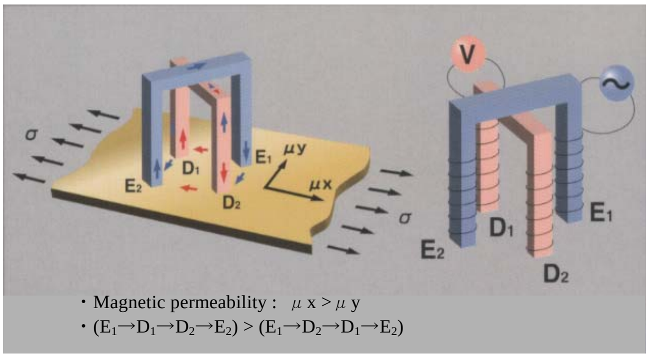


Fig.18 Principles of magnetic stress measurement using a magnetic anisotropy sensor

Fig.19 Magnetic stress measurement system

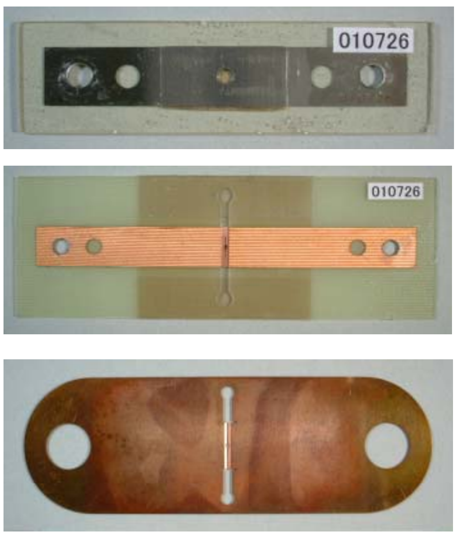


Fig.20 Fatigue sensors

6.3 Development of maintenance solutions

The optimized use of the massive amounts of social investment in steel structures is essential for planned maintenance and management. At the same time it is necessary to reconsider the concept of maintenance itself. The development of maintenance solution technology which enable the prediction of damage before the damage occur is strongly required (**Fig.21**), while conventional maintenance is naturally directed to maintaining the status quo.

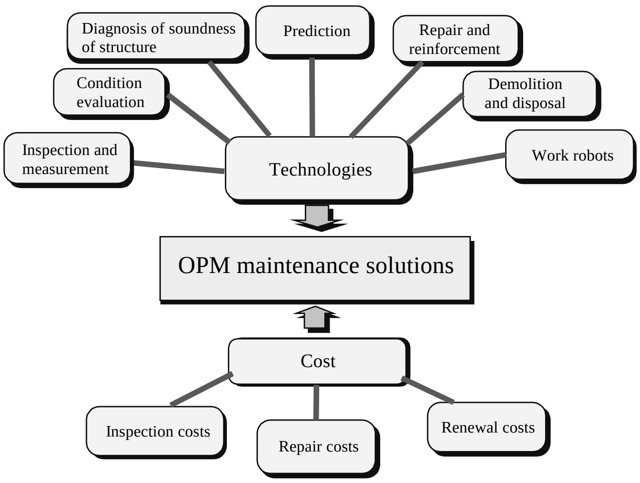


Fig.21 Development of NKK's maintenance solution operations

NKK has developed an optimized planning method (OPM: Optimized Planning for Maintenance) to provide maintenance solutions. This method seeks to provide technical forecasting at a practical level of accuracy over a given management period (e.g., 20 - 30 years) to minimize costs over this period, and to conduct planned, preventative, and strategic maintenance by taking into account the change of structural condition and the inspection results.

Based on this rational approach, this method indicates the quantitative and objective evaluation of the need of maintenance, and as a result it makes a structure's life longer. It means that a new value is created in older structures.

7. Conclusion

NKK has contributed much to the development of social infrastructure in such areas of highways, coastal civil works, rivers, and construction through its steel structures technologies and products. The current environment for investment in social infrastructure is in extremely severe situation. However within a framework of continuing need for infrastructure development, there is a need for cost reductions incorporating the viewpoint of lifecycle cost, and a long-term need to protect the country and population from disaster. These conditions therefore require systematic management and solutions, which incorporate design, as well as maintenance and management, and administration, together with conventional hardware.

The regeneration of the city in which a large proportion of the population live, and which is at the same time the center of economic and social activity, is a keyword in the direction of social infrastructure development for the future. In terms of urban environment, revitalization of the city center, and the urban residential environment, development of highways and other facilities which integrate the city with the surrounding areas must satisfy requirements for safety (e.g., seismic resistance), environment, construction work in the vicinity, amenities, scenery, and continuity with technology and products which employ the characteristics of steel structures as never before.

NKK's wide-ranging and sophisticated technical abilities will continue to contribute in answer to the varied requirements of the future.

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