UDC669.295.7:624/627

Application of Titanium to Construction and Civil Engineering

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Abstract:

Demand for titanium in the building materials market has been amazingly increasing. This demand growth is closely related to technology development. In the construction field, factors in the demand growth are market development waged on the initiative of titanium manufacturers, development of application technology undertaken jointly by titanium manufacturers, fabricators and constructors, as well as the advancement of fabrication technology and surface treatment technology as seen in anodizing, mirror polishing and blasting. Marine civil engineering is an area where titanium's excellent corrosion resistance can be best utilized but its cost competitiveness and ease of installation are must severely tested. This field has seen extensive research and development work by titanium engineers in cooperation with engineers specializing in civil engineering, corrosion protection and joining. One outcome of these R & D efforts is the application of titanium-clad steel as protective lining in the splash and tidal zones of steel piers for the Trans-Tokyo Bay Highway (TTB) Bridge. The progress in the past and future outlook of these titanium demand development efforts are described. Furthermore, several studies now under way are discussed, and the service performance of the titanium-clad steel lining of the TTB Bridge steel piers is reported.

1. Introduction

When Nippon Steel launched its titanium business in 1984, the company placed prime importance on the cultivation of new markets for titanium and the development of technology for that purpose. Particular emphasis was laid on the construction materials and civil engineering fields as target areas for expansion of the titanium business. The company's first undertaking in the construction materials sector was the development of a titanium roofing field seamless welding process. (The roofing work of a building at Maten Elementary School in Okinawa Prefecture, a region known for severely corrosive environment, was completed by the seamless welding process in 1985.) In the civil engineering sector, a process was developed to protect steel pipe piles from

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corrosion by the combined use of titanium and petrolatum. (In 1985, its testing was started on the littoral drift observation pier of the Ministry of Transport in Hasaki, Ibaraki Prefecture.) The two projects were the first attempts in the world as far as titanium is concerned, and gave an impetus to the growth of titanium usage in the construction and civil engineering fields.

Titanium is a metal that has almost perfect corrosion resistance in an ordinary natural environment. It is the same as stainless steel and aluminum in that corrosion resistance is provided by a passivated surface film (oxide film several tens of Angstroms in thickness). As shown in **Table 1**, titanium possesses remarkable corrosion resistance characteristics and, in particular, has complete corrosion resistance in the marine environment[1-5].

Table 2 shows the physical properties of titanium in comparison with those of other metallic materials used in construction applications. Titanium is lightweight, flexible, slight in dimensional change with heat and has many other excellent properties. It is as strong as carbon steel, nonmagnetic and nontoxic, does not easily ionize, and does not pollute the environment. It is an ideal metallic material for construction use. Its products are available as sheets, plates, tubes and pipes, wire rods and foil as well as titanium-clad steel plates. Wire rope, wire netting, expanded metal, bolts and nuts, and nails are among the secondary titanium products developed. Titanium products can serve a variety of applications in this way.

2. Problems with Development of Construction Material Market; Solution

Demand for titanium in the construction material market has significantly increased, mainly in the building sector, in the past few years, as shown in **Fig. 1**. As is the case with every new market, many problems resulting from inexperience had to be overcome in the construction material market.

Market development naturally depended heavily on the initiative taken by titanium manufacturers. Manufacturers' sales people asked customers (owners, architectural design offices, and general contractors) to consider the use of titanium in the design of their construction projects. The clients often asked them to guarantee the workability of titanium construction materials they supply.

When Nippon Steel's titanium product was adopted for use in a construction project, the company was asked to present the past record of use in previous projects. It was thus essential for the manufacturer to go through the entire course from trial manufacture to commercial application on a precisely planned basis, as shown in **Fig. 2**. Nippon Steel carried out joint development work with titanium fabricators and constructors, and in some cases also trained the clients' personnel in the use of titanium. (Titanium welding training sessions were held four times per year for a total of 24 times, and titanium fabrication and construction manuals were prepared.)

Table 1 Characteristics of corrosion resistance of titanium as construction material

Corrosion resistance by passive film	Corrosion resistance by thin (several tens of Angstroms) surface oxide film (TiO_2) or passive film. This film is extremely strong and stable.
Extremely high thermodynamic activity	Titanium has so strong binding force with oxygen that any localized break in oxide film is immediately repaired.
Stability against seawater	Titanium is stable against seawater, sea salt particles and chlorides, and does not suffer pitting corrosion or crevice corrosion in such environments.
Stable welded and worked parts	Weld heat-affected zones and cold-worked parts of titanium do not deteriorate in corrosion resistance.
Stability against acid rain	Titanium is stable against NO_X and SO_X and is not corroded by acid rain.
Stability against hot spring water	Titanium is stable against hydrogen sulfide and exhibits excellent corrosion resistance in hot spring regions[6].

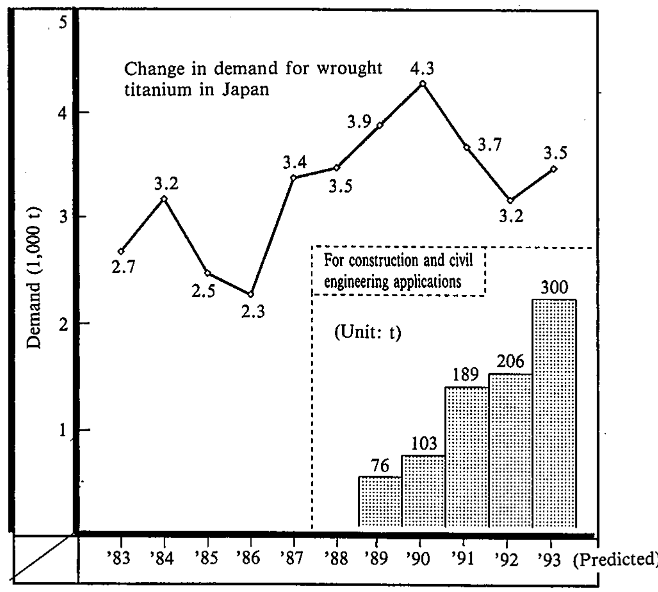

Fig. 1 Change in demand for wrought titanium in Japan (Japan Titanium Society)

Table 2 Comparison in physical properties of titanium with other metals

Property	Metal				
	Commercially pure titanium	Steel	Stainless steel (SUS 304)	Aluminum (5052)	Copper
Specific gravity	4.5	7.9	7.9	2.7	8.9
Melting point (°C)	1,668	1,530	1,400-1,420	593-649	1,083
Coefficient of linear expansion (cm/cm/°C)	8.4×10^{-6}	12×10^{-6}	17×10^{-6}	24×10^{-6}	17×10^{-6}
Thermal conductivity (cal/cm^2/s/°C/cm)	0.041	0.15	0.039	0.33	0.92
Electrical resistivity ($\mu\Omega$-cm)	55	9.7	72	5.8	1.724
Young's modulus (kg/mm^2)	10,850	21,000	20,400	7,030	11,000

3. Present State of Market Development in Building Construction Field, Future Outlook, and Research Reports

3.1 Present state of market development in building construction field

As previously noted, titanium has many favorable properties as a building construction material. Nippon Steel has developed applications for titanium to make the most of its excellent properties. Those applications developed are as listed in **Table 3** (civil engineering field included.)

Titanium is most frequently used for corrosion resistance, especially against sea salt particles. There are many other fields of application where corrosion resistance is expected from titanium, such as volcanic ash, hot spring fumes, acid pickling plants, industrial waste disposal plants, and electronic equipment manufacturing clean rooms. Recently, titanium has been highlighted as material for protecting cultural properties from acid rain. Titanium aesthetically colored by anodizing is finding increasing usage as a decorative material. Protection of cultural properties from acid rain and stability of colored titanium are described later. There are also such applications in which titanium is used for its light weight, nontoxicity, or its small dimensional change with temperature comparable with stone. In many applications, titanium satisfies two or more property criteria, demonstrating its amazing versatility.

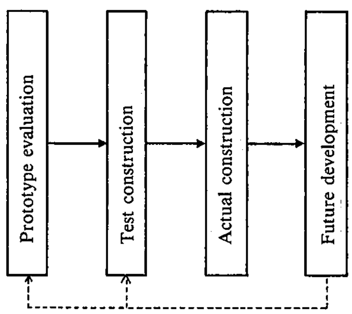

Fig. 2 Development steps

Recently, titanium has come to be used also in mild environment. In such applications, titanium is adopted to ensure the maintenance-free operation of buildings, and to prolong the service life of buildings by protecting their roofs and exteriors that are prone to atmospheric corrosion.

3.2 Market trends and outlooks in building construction field

Titanium was used for the first time as building construction material in the roof (90 tons) of the main sanctuary building of the Sekai Mahikari Bunmei Kyodan Headquarters at Izu in 1986. The following years saw the titanium demand in the same field shift between 70 and 90 tons per year. Then, in the years 1991/1992, the annual titanium use jumped to 200 tons, in which main factors were increased application as roofing material in such large public buildings as the Fukuoka Dome, a covered ball park (see **Fig. 1**). The figure is expected to exceed 300 tons in fiscal 1993 with the use of titanium in the exteriors and roofing of the administration and conference building at the Tokyo International Exhibition Center (see **Fig. 3**), and in ventilation tower exteriors in the Tokyo Bay route of the Metropolitan Expressway Public Corporation. The use of titanium is spreading from Tokyo, Osaka and Kyushu to nationwide from Hokkaido through Okinawa.

In the recent metal roofing and exterior market, demand for high-grade prepainted steel sheets and stainless steel sheets is rapidly growing, reflecting strong needs for high-grade materials with excellent durability. Seaside and other severely corrosive environments require materials with particularly high corrosion resistance, which translates into increasing usage of titanium.

Table 3 Properties and applications of titanium as construction material

Property/application		Example
Seawater and sea salt particle resistance	Offshore structures	Corrosion protection of steel piers of Trans-Tokyo Bay Highway Bridge; corrosion protection of existing steel pipe piles in piers in Kitakyushu Harbor
	Marine and littoral environment	Exterior: Ventilation tower of sunken-tube tunnel across Tamagawa River, Metropolitan Expressway; Tokyo International Exhibition Center
		Roofs: Aquariums in Niigata and Nagoya; Fukuoka Dome in Fukuoka; guard fences, windbreak fences, noise barriers
	Hot and humid areas, outlying islands	Roof of martial arts gymnasium in Okinawa Prefecture; fuel tanks and fire fighting equipment on Iwo Jima Island
	Marine facilities	Seawater strainers and piping at aquarium, International Ocean Exposition, Okinawa '75 (Expo 75); seawater intake strainers at power plants
	Undersea tunnels	Anchor bolts for Seikan Tunnel and New Kanmon Tunnel; line hardware (catenary drop arms and sea water sensors for New Kanmon Tunnel
Acid rain resistance		Repair of marble structures and cultural properties
Volcanic ash resistance		Roof and exteriors of prefectural government building, Kagoshima Prefecture
Hot spring water resistance		Bolts, nails, fixtures and roof of wooden buildings in Sugayu hot spring, Aomori Prefecture; ducts in Kaminoyama hot spring, Yamagata Prefecture
Corrosion and chemical resistance		Ducts at waste disposal plants; manhole covers and insect net at water purification plant, Hiroshima City
Ionization difficulty (dissolution difficulty)		Clean rooms
Low thermal expansion		Repair of marble structures, long roofs
Light weight		Manhole covers at water purification plant, Hiroshima City
Decorativeness		Monuments, temple roofs; building exteriors - mirror finish, anodizing color finish, alumina-blasted finish
Nontoxity		Water tanks; rain water utilization roofs at water purification plants and on outlying islands

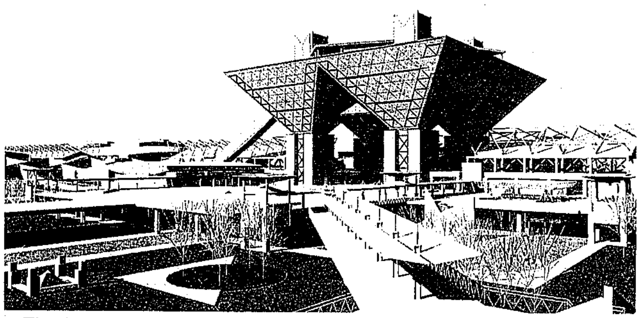

Fig. 3 Artist's impression of administration and conference building at Tokyo International Exhibition Center

There is strong concern about the future increase of maintenance cost. Materials with high corrosion resistance are always in strong demand in Japan that has long coastlines and many important construction projects are located at marine sites. Even for use in mild environments, there are mounting needs for long-term durability as aforementioned, which should continue to push up the demand for titanium.

3.3 Reports on studies of titanium application to buildings

Many studies have been made on the application of titanium as building material. Here are reported some studies concerning the color stability of colored titanium, and the application of titanium to monumental buildings.

3.3.1 Study on color stability of anodizing-colored titanium

Colored titanium is produced by growing an oxide film (colorless and transparent) on the surface of titanium by anodizing and developing color through light reflection and interference. Because of its aesthetic metallic luster, colored titanium is spotlighted as material for decorating buildings and monuments. The growth of the oxide film is apt to cause the discoloration of colored titanium under the special weather conditions of high temperature, high humidity, and high sea salt content. Titanium samples colored to gold and blue have been exposure tested in Ginowan, Okinawa Prefecture. Results of observation in the third year of exposure are reported here.

Fig. 4 shows the relationship of exposure time and the oxide film thickness[7]. The oxide film thickness was obtained from fitting between the theoretical and measured values of the chromaticity L*a*b* (JIS Z 8729) of the interference colors calculated by assuming that the refractive indexes of the film and the substrate are 2.5-0i and 2.89-3.35i, respectively, when the wavelength of incident light is 632.8 nm, and by considering the wavelength dispersion of the film and the substrate. Predicted relations between the film thickness and chromaticity are also shown.

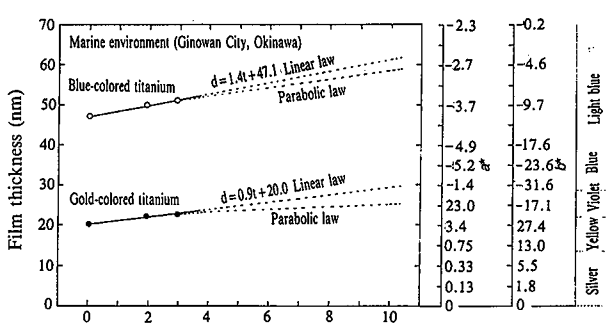

Fig. 4 Change with time in oxide film thickness of colored titanium in marine environment, Okinawa

The oxide film grows, though only slightly, with time. The blue-colored titanium slightly diminishes in color, while the gold-colored titanium slightly changes to violet. The blue-colored titanium covers a wider film thickness range and has a better long-term stability than the gold-colored titanium. The blue-colored titanium is predicted to retain the initial color for scores of years in the Okinawa marine environment, whereas the gold-colored titanium is expected to change to the violet color. Exposure test of colored titanium samples has been launched also in other parts of Japan. In the Honshu (Main Island) region where it is drier and cooler than in Okinawa, the gold-colored titanium will be able to retain the original color for a long period of time.

3.3.2 Study on titanium application to protection of cultural properties

Copper forms a heavy patina film on the surface and is favored as roofing material for shrines, temples, and other cultural properties. The recent deterioration of environment, particularly by acid rain, has created various problems with copper. Acid rain does not allow a stable film of basic copper carbonate (patina) to form but causes an unstable film of basic copper sulfate to form on the copper surface[8,9]. The basic copper sulfate film poses not only aesthetic but corrosion problems such as pitting corrosion (raindrop corrosion) where raindrops fall. It is also possible that copper is corroded by solutions leaching out of lime plaster and pine needle-smoked clay roofing tiles[9]. These forms of corrosion are grave problems for the protection of cultural properties, and are expected to prompt the substitution of titanium for copper. Blasting provides titanium with color and wettability comparable to those of pine needle-smoked clay roofing tiles. Such titanium goes well in harmony with Japanese houses and is considered usable with protected monumental buildings.

Photo 1 shows the results of raindrop corrosion simulation test involving dropping artificial acid rain (H_2SO_4:HNO_3:HC1 = 1.4:1:4 (molar ratio), pH = 4.6)[9]. Copper was corroded, but alumina-blasted titanium showed no change in surface condition after the test. The test verified the superior corrosion resistance of titanium in the acid rain environment.

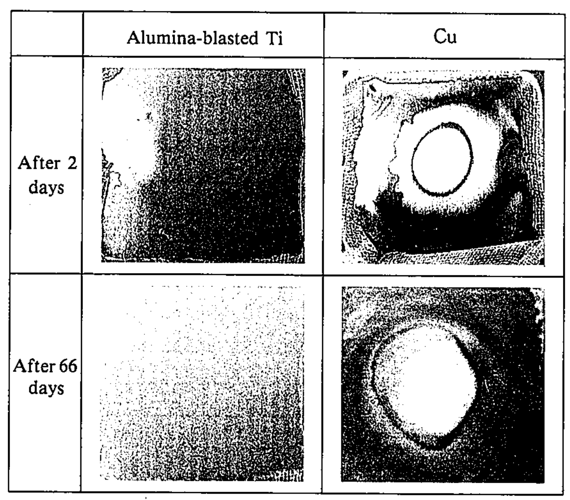

Photo 1 Metal surfaces after raindrop corrosion simulation test in artificial acid rain

4. Present State of Application Development in Civil Engineering Field, Future Outlooks, and Research Reports

4.1 Present state of application development in civil engineering field

Corrosion and deterioration of steel structures are extremely serious problems in the civil engineering field, particularly in marine civil engineering. There are strong needs for structural and lining materials that are reliable and strongly resistant to corrosion for a very long period of time. Application of titanium in this sector has just begun. Actual results in the construction field and results of exposure tests[1-5] show that titanium is the most promising metal in marine civil engineering applications. It has great potential in lining application for corrosion protection of steel structures. Use of titanium in corrosion-resistant applications is limited by its cost and therefore is conceivable only under special conditions now.

Cost competitiveness and service performance in actual environments are prerequisite for titanium to be adopted in the civil engineering sector. Many application and development projects are under way with a view to future progress, as listed in **Table 4.**

Several titanium products are already in the practical stage as they are used in some actual construction projects. A typical example is titanium-clad steel plates employed for lining the splash and tidal zone of steel piers of the Trans-Tokyo Bay Highway (TTB) Bridge (see **Photo 2**)[10-13]. The TTB project may be said to have ushered in the era of titanium application to protect offshore steel structures against corrosion to ensure their durability over a very long term. Two and a half years after their installation, the titanium-clad steel plates display beautiful titanium surfaces as if to demonstrate a central corrosion protection technology of marine civil engineering for the next century. Results of the first-year survey of the titanium-clad steel plates are outlined later.

Table 4 summarizes the present state and future outlook of titanium in civil engineering applications.

Table 4 Present development and future outlook of titanium in civil engineering field (Nippon Steel)

Application		Step	I	II	III	IV
			Prototype evaluation/ in-house test use	Practical use test	Commercial use	Future target
Corrosion protection of structures	① Steel structures	(1) Titanium lining (organic composite corrosion protection)	'85 Wharf piles at Nagoya Works	'85 Hasaki littoral drift observation pier piles '85 Oil drilling rig off Agano River	'90 Ministry of Transport Kitakyushu pier piles	Corrosion protection of existing steel pipe piles
		(2) Titanium lining (concrete composite corrosion protection)	'93 Protected steel pipe pile driving test			Steel pipe piles protected by both titanium and concrete Corrosion protection of concrete structures
		(3) Clad steel welding	'90 Kimitsu wharf exposure (steel pipe piles)	'90 Kimitsu port PSR[1)] steel pipe piles	'91 Trans-Tokyo Bay Highway (TTB) Bridge steel foundations (underwater foundations)	Corrosion protection of steel piers and caissons Corrosion protection of large floating structures Pile-supported reef
		(4) Titanium foil application (organic adhesive tape)	'93 TTB exposure test (Japan Titanium Society)	'91 Japan Highway Public Corporation Okinawa Yuzuruta bridge piers '88 Sugayu hot spring building roofs	'90 Nitto Denko Katsukawa employee hotel building roof	Corrosion protection of bridge girders Corrosion protection of gas tanks and other structures
	② Concrete structures			'91 Kashiwazaki snow drains (concrete composite panels)		Corrosion protection of concrete structures Forms left in place in concrete
Corrosion-resistant structural material	③ Tunnel facilities			'89 JR New Kanmon Tunnel catenary drop arms '92 JR Uetsu Tunnel atenary drop arms	'83 JR New Kanmon Tunnel seawater sensors JR New Kanmon Tunnel bolts and nuts	Development of tunnel facilities Application of titanium to underground space development Segment attaching bolts and nuts
	④Guard fences, etc.		'85 Ground level protection of steel sheet-welded utility poles	'89 Windbreak fences in Mishima fishing port, Yamaguchi Prefecture '90 Handrails in Hachijo Jima Island, Tokyo	'93 Hardware for rapid transit railroad stations in Metropolitan Waterfront Subcenter '85 Fire fighting equipment on Iwo Jima Island	Safety facilities with very high durability
	⑤ Seawater facilities			'87 Seawater intake screens at Oita Cooperative Thermal Power Plant '91 Mooring buoys and chains	'89 Expo 75 aquarium (seawater strainers)	Seawater intake screens, piping, etc. Seawater facilities and fittings
	⑥ Bridges		'92 Suspension bridge pins and bearings (Ti-Teflon)			Suspension bridge pins and cables

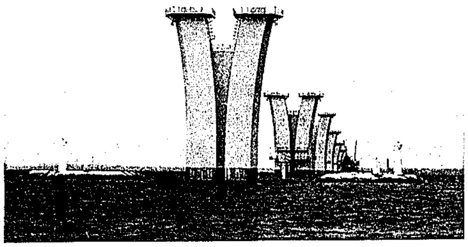

Photo 2 Trans-Tokyo Bay Highway Bridge steel piers (lined with titanium-clad steel plates above and below sea level)

4.1.1 Application development of corrosion protection lining method for structures

This method uses titanium as protective lining for the main purpose of vastly extending the service life of marine steel structures. It is generally employed in combination with conventional painting (in the atmospheric zone) and cathodic protection (in the submerged zone). How to fix the titanium lining to the steel structure is a problem. The methods whereby the titanium lining is fixed or joined to the steel structure to be protected may be classified as follows:

(1) A method whereby the titanium-clad steel plate is welded to the steel structure to be protected (as done for TTB Bridge steel piers).
(2) A method whereby the titanium lining is used together with corrosion inhibitor such as petrolatum and fixed by bolts and nuts or the like to the steel structure to be protected. This method can be applied to the corrosion protection of existing steel pipe piles, for example, as practised at the Kuzuha wharf of the Kitakyushu Harbor (see **Photo 3**).
(3) A method whereby a protective tape of titanium film and adhesive is applied to the structural member to be protected. This method has been used on the roofing of buildings and is under test in civil engineering applications in various parts of Japan.
(4) A method whereby the structure to be protected is lined with titanium sheet and the gap between the structure and the titanium sheet is filled with concrete or the like.

4.1.2 Development of titanium as corrosion-resistant structural material

Application of titanium as structural material is seriously hampered by its high cost, as previously noted. Titanium has been used as structural material under special conditions. Such applications are described below, together with reasons for selection.

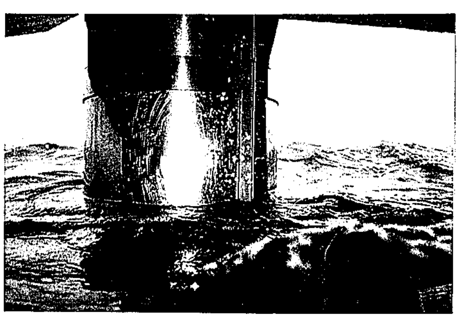

Photo 3 Steel pipe piles lined with protective titanium sheet in Kitakyushu Harbor (barnacles removed in second year of operation)

West Japan Railway is studying the use of titanium in aerial line hardware or catenary drop arms (see **Photo 4**) for the New Kanmon Tunnel of the Shinkansen. The substitution of titanium for steel was made on the basis of good results obtained in a four-year practical application test, and from the consideration of various constraints on installation and maintenance work in the tunnel. Essentially in the catenary drop arm installation in a tunnel, time factor constraints are large and the labor cost ratio is very high in the total installation cost. Titanium catenary drop arms may incur about 2.5 times more than their steel counterparts (galvanized and painted) in material cost, but their use is fully justified when their long service life is taken into account. Titanium catenary drop arms also meet the strong need for a maintenance-free permanent structure that does not damage the tunnel lining. Study is under way for their use also in land tunnels.

Titanium handrails are used in seacoast parks for safety and aesthetic reasons. Seawater intake screens made of titanium were exposure tested at the Oita Cooperative Thermal Power Plant. The screens tested performed well in the prevention and removal of barnacle buildup. It will not be long before they are brought into practical use.

Those cases in which titanium is adopted as corrosion-resistant material may be summarized as follows:

(1) Maintenance is difficult to perform and installation work accounts for a large percentage of the total project cost.
(2) Auxiliary facilities must be constructed as permanent structures so that principal structures like tunnels and underground structures are not damaged by maintenance.
(3) High reliability to assure long-term durability is required of safety facilities.
(4) There is an aesthetic need to meet.
(5) Maintenance involves operation stoppage, resulting in a large economic loss.

4.2 Future targets and outlooks

Future development targets to meet the strong needs for corrosion protection in the marine civil engineering area may be summarized as follows:

(1) Protective lining methods for steel structures
   i) Development of corrosion protection method for offshore

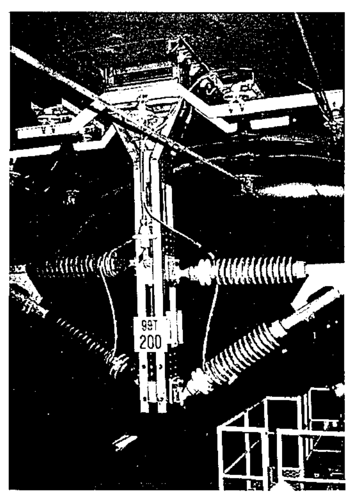

Photo 4 Titanium catenary drop arm in New Kanmon Tunnel

structures, such as steel bridge piers, caissons and jackets, over a very long period of time

ii) Development of corrosion protection method for large floating structures

iii) Development of corrosion protection method using titanium foil tape for severely corroded portions or difficult-to-repair portions of bridges and other structures

iv) Development of method of corrosion protection for steel cables for long bridges

(2) Corrosion-resistant structural materials

i) Development of undersea tunnel auxiliary equipment and segment attaching bolts, etc.

ii) Development of titanium application in underground space development

iii) Development of maintenance-free safety facilities

iv) Development of titanium cables (with high strength and light weight) or titanium-clad steel wires for long bridges

(3) Development of corrosion protection method for concrete structures

4.3 First-year survey of Trans-Tokyo Bay Highway Bridge steel piers protected with titanium-clad steel lining

As described earlier, 5-mm thick titanium-clad steel plates (1 mm of titanium plus 4 mm of steel) were welded to the splash and tidal zone of each of 12 steel piers of the Trans-Tokyo Bay Highway (TTB) Bridge as protective lining to ensure a very long service life of 50 to 100 years[10-13].

The P7 pier, the first to be lined with the protective titanium-clad steel plates, was investigated one year after the construction. The items of investigation were the visual observation of titanium-clad steel plate surfaces, welds and painted titanium areas and the condition of cathodic protection as determined by potential measurement of the titanium-clad steel plates.

The investigation was conducted in July, a month when shells grow. The titanium surfaces in the splash and tidal zone were covered with many barnacles, and the plain titanium surfaces, painted titanium surfaces and aluminum alloy galvanic anodes in the submerged zone were covered with blue mussels. When these macrofouling organisms were removed, the plain titanium surfaces, welds, and painted titanium surfaces exhibited no abnormality.

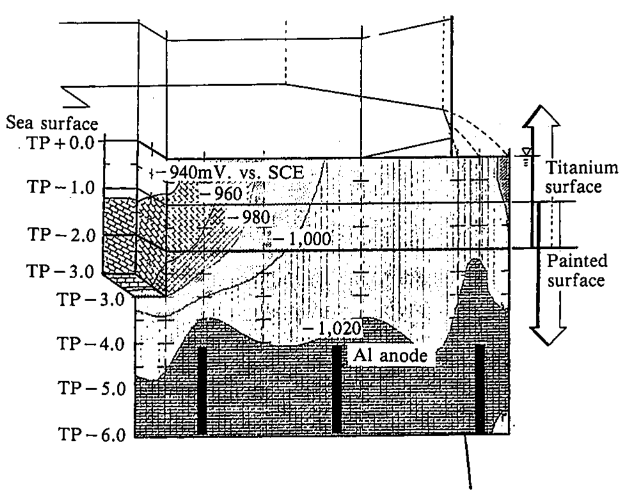

Fig. 5 Potential distribution near titanium surface of pier P7[14)]

The potential of the titanium surfaces in the submerged zone was measured with saturated calomel standard electrode (SCE) and potentiometer. The measuring range was one-quarter of the pier circumference on the Kisarazu side from the sea surface (TP ± 0) to the depth of 6 m (TP − 6).

The measured potential distribution is as shown in **Fig. 5**[14)]. The highest potential was measured on the valley farthest from the aluminum alloy galvanic anodes, but satisfied the design protective potential of − 770 mV or less (vs. SCE). It was confirmed that the contact areas between the titanium and steel portions, originally considered susceptible to corrosion, were totally protected against corrosion[14)].

5. Conclusions

The accumulation of social capital investigation is indispensable for constructing a comfortable, cultural society, but on the other hand it increases the maintenance cost of the accumulated social capital. It is a strong public concern that the increasing maintenance cost may suppress the amount of capital available for new investments. A very small amount of investment in maintenance-free facilities at present will increase new investment capacity in the future. In other words, it is one of today's most important issues not to leave the maintenance burden of social capital for the next generation.

Titanium assures maintenance-free operation over a very long period of time, has no adverse impact on the environment, and thus has a great potential in the construction material market. Work will be continued to develop new applications for titanium as construction material.

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