# Next Generation Trans-Strait Road Projects and the State of Technology Development

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## ABSTRACT

Super long-span bridges between 20 and 30% greater than the Akashi Kaikyo Bridge need to be constructed in order to create new traffic axes to enliven and stimulate outlying regions of Japan for the 21st century. Studies have been undertaken to develop ways to construct super long-span bridges more economically and rationally. As the results, new types of structures, new concepts of designs, and innovative execution technologies have been introduced, permitting the construction of super long-span bridges at much lower cost than by simply extending and applying existing technologies.

*Key Words : Trans-Strait Road Projects*
*Super Long-Span Bridges*
*New Types of Structures*
*New Concepts of Designs*

## 1. INTRODUCTION

The Akashi Kaikyo Bridge, the longest one among not only bridges between Honshu and Shikoku but also all bridges in the world, opened on April 5, 1998. When the Kurushima Bridges and Tatara Bridge will open as scheduled in the spring of 1999, Honshu and Shikoku will be linked completely by the three routes as envisioned in the original plans.

New traffic axes are being advocated as the key to making effective use of the limited land area of Japan to provide this country with a more balanced national land structure for the 21st century. And the lessons learned by the Hyogo-ken Nanbu Earthquake have shown us that the redundancy in infrastructures is extremely important.

For such backgrounds, new traffic axes to play a key role in creating newly defined multi national land axes to enliven and stimulate outlying regions of Japan occupy the following position in the "New Comprehensive National Development Plans" authorized by the Japanese Government in March, 1998. The Tokyo Bay Mouth Road, Ise Bay Mouth Road, Kitan Strait Road, Kanmon Strait Road , Hoyo Strait Road and Shimabara-Amakusa-Nagashima Bridges projects, that should be implemented with close attention paid to cost-benefits effects and other related conditions, are planned to promote the development of new technologies including those that reduce the cost of long-span bridges construction, to protect their surrounding environments, and to stimulate outlying regions by promoting increased cooperation and interaction among regions.

Figure 1.1 presents trans-strait road projects now at the concept stage.

To complete the Akashi Kaikyo Bridge and other Honshu-Shikoku Bridges, new technologies of various kinds were developed, permitting the construction of safe and

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reliable long-span suspension bridges in the 2,000m class. It will be necessary to apply even more advanced versions of these technologies in order to construct the next generation projects.

But the meteorological and oceanographic conditions in terms of topography, geology, water depth, wind speed and so on at the planned sites of future projects are expected to be severer than those at the Seto Inland Sea area where the Honshu-Shikoku bridges were constructed. Since the straits to be crossed will be wider and deeper, planned bridges will require superstructures with longer spans and substructures appropriate for deeper water. Faced to the Pacific Ocean, they will be vulnerable to the effects of typhoons and ocean waves. They must also be constructed in earthquake prone area. Considering these conditions, it has been concluded that super long-span bridges constructed as the part of future projects will be between 20 and 30% longer than the Akashi Kaikyo Bridge. It is believed that it would be technically possible to use the same technology applied to the construction of the Honshu-Shikoku bridges to build bridges greater than ever before, but to build them more economically and rationally, newer technologies must be developed.

## 2. OUTLINES OF TRANS-STRAIT ROAD PROJECTS

Three trans-strait road projects, namely the Tokyo Bay Mouth Road, Ise Bay Mouth Road, and Kitan Strait Road, are introduced below.

### 2.1 Tokyo Bay Mouth Road

The Tokyo Bay Mouth Road is about 20km long trans-strait road (marine section : about 10 to 15km) crossing the Uraga Strait to link the Yokosuka-shi in Kanagawa-ken with the Futtsu-shi in Chiba-ken.

The Uraga Strait is an international navigation channel (channel width : 1,750m) where ships converge. The Tokyo Bay Mouth Road will be constructed close to the location of the epicenter of the Great Kanto Earthquake of 1923.

The bridge now under consideration is a long-span suspension bridge with a center span length of 2,250m.

### 2.2 Ise Bay Mouth Road

The Ise Bay Mouth Road is about 90km long trans-strait road (marine section : about 20km) crossing the Ise Bay Mouth from Irago Cape at the tip of the Atsumi Peninsula in Aichi-ken to the Shima Peninsula in Mie-ken.

The Ise Bay Mouth is a strait designated as an international navigation channel (channel width : 1,200m). Plate boundary-type earthquakes of Magnitude 8 class occurred near the planned site around 1945, and there is a fear of the Tokai earthquake near the route.

The plan now under consideration hypothesizes a long-span suspension bridge with a center span length of 2,000m.

### 2.3 Kitan Strait Road

The Kitan Strait Road is a trans-strait road with a length of about 40km (marine section : about 11km) linking the Wakayama-shi in Wakayama-ken with the Sumoto-shi in Hyogo-ken.

The Kitan Strait Road locates parallel to the Median Tectonic Line where the high level of activity is forecast and close to the epicenters of the Nankai Earthquake and other plate boundary-type earthquakes.

The study underway in preparation for the construction of the bridge over the Kitan Strait hypothesizes a long-span suspension bridge with a center span length of 2,700m. Figure 2.1 shows the planned route and Figure 2.2 shows the Kitan Strait Bridge.

## 3. INTRODUCTION TO NEW TECHNOLOGICAL DEVELOPMENTS

3.1 Introduction to New Technological Developments

Priority and preferential studies of technologies believed to have the potential to contribute to the shortening of construction period and reduction of construction cost are now in progress.

The major technological developments that have been promoted are broadly categorized into three groups : 1) new types of structures, 2) new concepts of designs, and 3) innovative execution methods. An outline of these technological developments is presented in Table 3.1.

3.2 New Types of Structures

(1) Girder Sections with Lower Cost and Better Aerodynamic Stability

It is vital to guarantee that super long-span suspension bridges remain stable during strong wind conditions. Methods of guaranteeing aerodynamic stability include increasing the stiffness of stiffening girders and devising innovative new girder sections.

For the Akashi Kaikyo Bridge, a truss type stiffening girder already used in earlier bridges has been adopted. And because of their small center span lengths of about 1,000m, single box type stiffening girders have been used for the Kurushima Bridges.

Problems that must be overcome to construct super long-span suspension bridges with a center span length greater than 2,000m include 1) the steel weight increase caused by measures to increase the stiffness of the stiffening girders and 2) the truss girders are vulnerable to the effects of wind by the high drag force. To overcome these problems, studies now in progress are focused on the use of slotted box girders and single box girders on two premises: 1) the use of box girders will improve the wind resistance, improving the vibration properties and aerodynamic properties and 2) it is possible to construct a superstructure using the hoisting erection method that raises the box girder blocks directly from the sea surface at the erecting location.

(2) Underwater Foundations with Lower Cost and Better Earthquake Resistance

Comparisons of the planned sites of future projects with those of the Honshu-Shikoku Bridges reveal that 1) the former tend to be closer to the epicenters of large scale earthquakes, 2) their foundations must be constructed in deeper water, 3) and the properties of the bearing ground supporting their foundations are worse than in the case of earlier bridges. It will, therefore, be necessary to develop underwater main tower foundation types that are of more highly earthquake resistance and more economical and rational to construct than existing cylindrical solid foundations (the main tower foundations of the Akashi Kaikyo Bridge for example).

Studies to meet these needs are based on the twin-shaft type foundation shown in Figure 3.1. The benefits of this type include 1) lower concrete volume that reduces construction cost and shortens construction period, 2) the light weight that allows its use on relatively softer ground, and 3) the light weight and lower center of the gravity for superior earthquake resistance. It is essential that future projects be preceded by studies to determine the shape most appropriate for each project considering design and construction conditions such as the water depth, geology and so on at the planned sites.

3.3 New Concepts of Designs

(1) Wind Resistant Design

While the Honshu-Shikoku Bridges were being designed, a number of wind resistant design methods for long-span bridges were studied and tested experimentally to improve design precision. The knowledges obtained from the results of the full model wind tunnel studies conducted to study the aerodynamic stability of the Akashi Kaikyo Bridge in particular has been applied to propose a number of new concepts that may be incorporated into wind resistant design of future super long-span bridges.

[1] Review of Wind Fluctuation Characteristics

As the span length of bridges increases, the cross section of girders will be determined in accordance with wind load. It is, therefore, possible to create more economical and rational designs by improving the precision of wind load calculations.

Wind load is calculated by increasing the static load calculated from mean wind speed accounting for the effect of wind fluctuation. The results of the full model wind tunnel tests of the Akashi Kaikyo Bridge and observations of natural winds have confirmed that it is possible to achieve a relative reduction of the effect of wind fluctuation acting on the girder of a long-span suspension bridge. In other words, the wind load used to design super long-span suspension bridges can be lower than that calculated based on conventional standards.

[2] Development of Flutter Analysis

Aerodynamic stability of long-span suspension bridges has been studied based on wind tunnel tests in use of a section model supported by spring, but it is now known that since the span of bridges has increased, it is impossible to fully reproduce their behavior using a section model. For this reason, the wind resistant design for the Akashi Kaikyo Bridge involved the clarification of aerodynamic stability by conducting the wind tunnel tests using the 40m long full model to reproduce the complex vibration properties of the real bridge. The findings of this studies have permitted the development of a flutter analysis to be used to precisely clarify the aerodynamic stability of a long-span bridge.

(2) Seismic Design

It has been pointed out that future projects sites are close to the epicenters of large scale plate boundary-type earthquakes and the existence of active faults in the vicinity. It is, therefore, necessary to adopt appropriate design earthquake ground motions and corresponding analytical methods so that it will be possible to practice economical and rational design and will guarantee the aseismicity of the structures.

[1] Basic Concepts of Seismic Design

As a basis of seismic design, the design earthquake ground motions and the corresponding safety levels of structures will be considered at two stages. At Level-1 (L1), "damages which destroy transportation functions shall be prevented for moderate ground motions induced in the earthquakes with high probability to occur within the life time of structures". At Level-2 (L2), "recoverable functional damages shall be allowed, but collapses shall be prevented for extreme ground motions induced in the earthquakes with low probability to occur at future projects sites."

[2] Input Design Earthquake Ground Motions

The input design earthquake ground motion used for L1 design is evaluated by statistically analyzing past earthquakes within 300km of the center of future projects sites to hypothesize ground motion with return period of 150 years.

The input design earthquake ground motion used for L2 design is evaluated on the hypothesis that either large scale plate boundary-type earthquakes or inland intra-plate earthquakes caused by active faults will occur relatively close to future projects sites. This ground motion is evaluated in some ways : 1) attenuation equations, 2) fault rupture process models, 3) recorded strong ground motion at near field of large scale earthquakes.

[3] Seismic Design Methods of Foundations

The seismic design of foundations is

conventionally done based on the response spectrum method : the use of a rigid body using a two-degree-of-freedom model that represents soil stiffness as a linear spring. But because it is clear that during a large scale earthquake, the stiffness and damping properties of surrounding soils produce nonlinear behaviors, the L1 seismic design method that accounts for these properties has been developed. It is, therefore, now possible to perform high precision rational seismic design of foundations.

The check of the stability of foundations against L2 ground motion is made by elasto-plastic FEM time history response analyses. In the analyses, the nonlinear stress-strain relation of surrounding soils is modeled as the modified Ramberg-Osgood model, and a model that can represent the characteristics of the separation between a foundation and ground is used. The properties of ground are analyzed in detail by this method.

(3) Design of Superstructures

In superstructure design standards of the Honshu-Shikoku Bridges, provisions contributing substantially to lower construction cost and shorter construction period have been reviewed.

[1] Allowable Stress of Main Cables

Because the weight of main cables in a super long-span suspension bridge with a span length exceeding 2,000m will account for between 20 and 30% of the steel weight of the bridge, and lowering the weight of main cables will make a large contribution to lowering construction cost and shortening construction period.

The design of main cables in the Honshu-Shikoku Bridges were adopted as the allowable stress of 56kgf/mm$^2$ for the Innoshima Bridge (completed in 1983) and 64kgf/mm$^2$ for the Seto-Ohashi Bridge (completed in 1988). In the design of the Akashi Kaikyo Bridge, because the cable strands material was improved to increase the tensile strength from 160kgf/mm$^2$ to 180kgf/mm$^2$, the allowable stress was raised to 82kgf/mm$^2$.

In the design of super long-span suspension bridges, it was found that the allowable stress of main cables could be set at 100kgf/cm$^2$ on such grounds as, 1) the quality of high strength strands material will stabilize, 2) bridge erection will have high precision, 3) corrosion prevention technologies will be sure to have improved, and 4) there will be leeway considering the safety balance of an entire suspension bridge system.

A comparison of the allowable stress of main cables with a case where it would be identical to that of the main cables of the Akashi Kaikyo Bridge (82kgf/mm$^2$) reveals that the weight of main cables can be lowered by about 40%.

[2] Methods of Live Loading

The design live load of super long-span suspension bridges is based on a calculation method that reduces live load according to the span in the same way as the design of the Honshu-Shikoku Bridges. And the method of loading only a traffic lane width instead of loading a carriage way width is adopted to account for the real situation of motor vehicle traffic.

Main towers have conventionally been designed by performing influence line loading : loading live load in a loading range that represents the severest possible conditions on the design section. But because it is highly unlikely for such loading conditions to actually occur, it is clearly possible to increase the allowable stress.

(4) Design of Substructures

Because the selection of the bearing layer to support a foundation is governed to a great degree by the dimensions of a foundation, the quantity of soils to be excavated to reach the bearing layer, etc., this is an important matter in determining the construction cost and period. To practice an economical and rational design, the bearing capacity of ground and deformation of a foundation must be precisely calculated and reflected in the design.

Accordingly, the method involving the clarification of the on-site ground properties through geological explorations and laboratory tests, the precise modeling of the results, and FEM analyses accounting for these ground properties have been developed. Specifically, 1) the geological properties of ground are clarified by acoustic explorations, boring explorations, or borehole loggings at the site, 2) the undisturbed specimens obtained by boring are used to clarify the deformation properties of ground from a minute strain level to a failure range, and 3) the nonlinear properties of ground are modeled and analyzed based on the results of the first two steps.

### 3.4 Innovative Execution Methods

#### (1) Execution Methods of Superstructures

Execution methods of superstructures have been introduced existing execution methods from other countries. Examples include 1) the use of tension bolts to assembly tower shaft joints, 2) the use of the hoisting erection method to install girder blocks, and 3) finishing tower bases with grouting. Other methods under consideration are the systematic overlapping of work steps by, for example, simultaneously erecting hanger ropes and girders, a main cable erection method that does not require catwalks, and more economical use of tower erection cranes.

#### (2) Execution Methods of Substructures

Maritime conditions will be particularly severe at the sites of future projects : ones to be constructed facing the Ocean where they will be exposed to the effects of typhoons and ocean waves. Execution methods that minimize the effects of the maritime conditions at the sites in order to improve working days ratio under these severe conditions now being studied include the use of semi-submersible pontoons immune to the effects of waves, the prefabrication of caissons and other steel members, and so on.

### 3.5 Effect of New Technological Developments

A comparison of the results of the trial design performed using newly developed technologies with that based on existing technologies has confirmed that new technological developments have been effective.

Table 3.2 presents the comparison of the results for the Tokyo Bay Mouth Bridge. It indicates that it is possible to reduce construction cost roughly by 30 to 50% in case developing new technologies are utilized. The factors for this reduction are presented below. But assuming that the factors overlap, the percentages representing the contributions of each new technology to the reduction of construction cost are just rough yardsticks.

1) Developments of new types structures (about 25%)
- Adoption of a slotted box girder (with an open grating)
- Adoption of a twin-shaft type foundation

2) Introduction of new concepts designs (about 10%)
- Reduction of wind load
- Classification of design earthquake ground motions at two stages
- Review of safety factors
- Appropriate evaluations of bearing capacity of ground

3) Innovative execution methods (about 5%)
- Review of fabrication precision and introduction of overlapping execution works
- Improvement of submarine drilling and working days ratio

The developments of new types structures contribute greatly to the construction cost reduction.

## 4. SPECIFIC EXAMPLES OF NEW TYPES STRUCTURES

4.1 New Types of Superstructures

(1) Slotted Box Girders

[1] Development of girders with better aerodynamic stability

A slotted box girder has an opening at the center of girder. Section models premised on a center span length of 3,000m with two side spans of 1,500m have been used for wind tunnel tests to study the relationship of the flutter onset wind speed with the opening pattern, opening width and aerodynamic appendages.

The results have revealed the following facts.

1) Aerodynamic stability is improved by providing an opening at the center of girder, and the larger the width, the better aerodynamic stability.

2) It is possible to improve aerodynamic stability by installing center barriers in the center of the opening.

3) It is possible to improve aerodynamic stability by installing guide vanes at the end of girder.

4) Guard rails contribute to improved aerodynamic stability and it is possible to improve aerodynamic stability during negative angle of attack by installing under barriers at the bottom of girder to create vertically symmetrical cross sections.

Figure 4.1 shows a cross section proposed based on the results of the wind tunnel tests.

[2] Developments of girders with lower cost

The central part of a slotted box girder must be provided with an opening as a wind resistance measure (the solidity factor of the opening is about 50%). But it is more economical and rational to provide the necessary opening width by installing an open grating to permit motor vehicles to drive on the top of the open grating than to provide the width of traffic lanes on the top of box girder. The girder with an open grating sharply cuts construction cost and shortens construction period. Specifically, 1) a main tower interval need not be expanded, 2) a foundation width need not be increased, and 3) the steel weight of a super long girder can be reduced.

The number of traffic lanes of future projects is assumed to be four lanes. In this case the central two lanes will have to be located on the open grating. The adoption of a slotted box girder will also permit stage construction, as the first two lanes are opened on the top of box girder and two more lanes are added later after an open grating has been installed.

In Japan, open gratings have been installed on some long-span bridges, such as the Seto-ohashi Bridge and the Akashi Kaikyo Bridge. But because they were introduced to guarantee aerodynamic stability, they were installed on parts of these bridges that normally load no traffic such as the central strip and road shoulder. They have never been used to form a roadway. Table 4.1 presents some examples of their use as a roadway in foreign countries. Photograph 4.1 shows the open grating of the Mackinac Bridge in the United States. It has not been replaced during the forty years since it was constructed.

At the PWRI, driving tests are planned to confirm the running safety of motor vehicles to travel at high speed on open gratings. The tests will be carried out to study 1) skid resistance on open gratings, 2) running safety when road surface conditions differ between the left and right wheels of motor vehicles (when changing lanes for example), 3) human engineering verification during driving on them (riding comfort, uneasiness experienced by drivers and so on), and 4) traffic management measures (speed limits and so on), etc.

Skid resistant tests are now underway (Photographs 4.2 and 4.3). The tests are being done with two kinds of open gratings : the open grating used at the Akashi Kaikyo Bridge and the open grating with notches formed on its lattice members surface to increase skid resistance.

The tests were done with the Test Vehicle running to the direction of the principal members of the open gratings and with the Test Vehicle running at right angles to the direction of these members. And sprinklers were used to reproduce rainy weather conditions in order to test their skid resistant properties during rainfall.

Figure 4.2 shows the results of the tests. The results reveal the following facts, 1) the sliding friction coefficients of gratings are smaller at slow speeds than at high speeds, 2) the notches on the gratings surface can slightly improve their sliding friction coefficients, 3) a lane changing can be performed surely for a motor vehicle running in the same direction as that of the principal members, but braking is more unsurely, 4) it is necessary to develop an open grating that provides far greater safety when braking and changing lanes.

It has also been confirmed that the adoption of a slotted box girder with an open grating will reduce the steel weight of girder by about 30% from the weight of a truss girder. This weight reduction will encourage the rationalization of main cables, main towers and substructures, permitting an entire suspension bridge to be constructed more economically and rationally.

It is now assumed that only the center of girder will be open gratings, but girders with the entire roadway width formed by open gratings (that is, all-grating girders) are also under consideration. The adoption of these types would permit both sharp reduction in the steel weight and large cost saving.

(2) Single Box Girders

It is considered that it would be difficult to guarantee a flutter onset wind speed (hypothetically 80m/s) on a center span length longer than 2,000m by adopting single box girders without improvements.

So studies are now being conducted in an effort to improve vibration properties of super long-span suspension bridges by connecting the main cables to the stiffening girder with cross-hangers (Figure 4.3) crossing over the deck to restrict the structural torsion.

The cross-hangers under consideration are a steel box type and cable type. A steel cross-hanger is also effective against compressive force.

Flutter analyses have been carried out, confirming their effectiveness. The cross-hangers would be installed at the locations shown in Figure 4.4 in the case of a super long-span suspension bridge with a center span length of 2,500m with two side spans of 1,250m. The flutter analyses results have demonstrated that the flutter onset wind speed is improved by about 10m/s by the single box girder with cable cross-hangers from that of the bridge without the system about 60m/s and by about 20m/s by the single box girder with steel cross-hangers.

But to design the single box girders with steel cross-hangers, it is necessary to overcome problems related to the connection between cross-hangers and girder and the structural details of cross-hangers intersection part.

4.2 New Types of Substructures

(1) Main Tower Foundations for Super Long-Span Suspension Bridges

To propose a main tower foundation for super long-span suspension bridges, research has been focused on the following items that are assumed to contribute significantly to saving cost to study a structure created by improving the twin-shaft type foundation shown in Figure 3.1.

[1] Rationalizing the large foundation design methods

The use of the seismic design methods

and substructural design methods described in 3.3 permits more rational foundation design.

[2] Improving the shape of foundations

The adoption, premised on design method rationalization, of a drastic structural shape that achieves a sharp reduction in the body quantities will sharply lower cost.

[3] reducing the quantity of submarine drillings

To cut the cost of submarine drillings, studies must be carried out to develop substructural design and construction methods that eliminate the need for submarine drillings.

[4] Adoption of reinforced concrete main towers

The adoption of reinforced concrete main towers will lower cost by rationalizing the reinforced concrete tower's construction method. And the construction of reinforced concrete towers will result in large reduction in the size of tower foundations made possible by the smaller dimensions of main tower's bottoms.

[5] Rationalization of concrete works

The concrete works that accounts for the principal share of the cost of substructure works must be rationalized by, for example, devising new execution methods or structures that do not require the use of a concrete plant barge.

Figure 4.5 shows a hybrid caisson foundation that has been proposed as a new structure that will permit these improvements.

A hybrid caisson foundation is a structure that transmits tower reaction forces from the top slab made of reinforced concrete to ground through the caisson wall that is a combined steel and concrete structure. The wall, a type called a full sandwich structure, is formed by casting highly flowable concrete between steel plates with stiffeners. The adoption of the full sandwich structure can save labor by eliminating the need to assemble reinforcements and to compact fresh concrete. The main towers are made of reinforced concrete for lower cost and continuity with a foundation. To minimize the quantity of expensive underwater concrete used, the interiors of the caissons are filled with sea water instead of underwater concrete. This type also can reduce ground reaction forces and permits a shallower bearing layer.

Another innovation being studied is a measure to reduce foundation size and eliminate the need for submarine drillings by spreading crushed rocks and grouting in their mound, forming a skirt on the bottom surface of a foundation, and inserting the skirt into the mound.

Figure 4.6 shows the work procedure.

(2) Anchorages for Super Long-Span Suspension Bridges

Figure 4.7 shows an anchorage with the splay saddle mount and anchor block separated. A splay saddle mount and anchor block is separated to reduce the quantity of concrete used. The bottom surfaces of both are inclined to minimize sliding forces.

Downward inclined compressive force produced by the bending in main cables acts on the splay saddle mount. So it is designed with the axis of the member oriented in this direction to transmit this force directly to ground. The adoption of this shape can reduce the size of the body and the maximum ground reaction force to install it vertically on ground in the direction of the force.

The anchor block is the part that resists the huge horizontal force of main cables. Inclining its bottom surface can reduce the quantity of concrete used while satisfying the required sliding safety factor.

Figure 4.8 presents the execution procedure.

The anchor block and splay saddle mount are prefabricated separately as reinforced concrete caissons, and after they are towed to the site by tug boats and installed at the fixed location, concrete is casted inside them respectively. In anticipation of cases that the reinforced concrete caisson of the anchor block will be too heavy to be executed while floating and setting, a method of dividing the anchor block in some parts then joining them on the water is under study.

Technical issues that must be resolved for this anchorage type include preliminary submarine drillings, inclining of the bottom surface related to concrete works, and others.

## 5. CONCLUSIONS

The studies have shown that new technologies such as developments of new types structures, introduction of new concepts designs and innovative execution methods will permit the construction of super long-span bridges at much lower cost than if existing technologies were applied.

Further studies of new structures, design methods, and execution methods are necessary in order to achieve even lower construction cost and shorter construction period.

And for each project, the investigations of natural conditions at the planned sites will be continued and reinforced. Then based on their results, the studies will be made to make the design and construction plans more economical and rational in the view of the unique local situations.


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*Table 4.1 Suspension Bridges with Open Grating Used as Roadway*

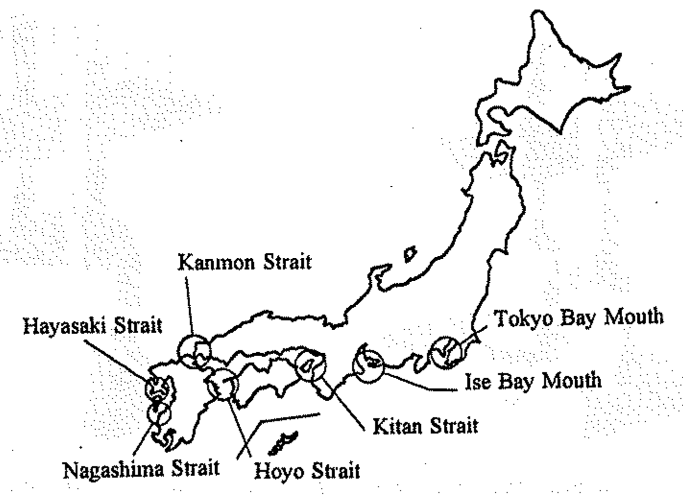
| Bridge | Country | Center Span Length(m) | Year Completed | Location of Open Grating | Purpose |
|---|---|---|---|---|---|
| New Tacoma Br. | US | 853 | 1948 | Lane boundaries | Aerodynamic stabilization |
| Mackinac Br. | US | 1,158 | 1957 | Sidewalks, inside lanes | Aerodynamic stabilization |
| Salazar Br. | Portugal | 1,013 | 1966 | Inside lanes | Aerodynamic stabilization |
| Angostura Br. | Venezuela | 712 | 1967 | Inside lanes | Weight reduction<br>Aerodynamic stabilization |

*Table 3.1 Outline of Technological Developments*

| Item | | Outline of technological developments |
|---|---|---|
| Developments of new types structures | Girder sections with lower cost and better aerodynamic stability | Studies of slotted box girders with an open grating at the center of girder and single box girders with cross-hangers for lower cost and better aerodynamic stability. |
| | Underwater foundations with lower cost and better earthquake resistance | Studies of underwater main tower foundations and anchorages for lower cost and better earthquake resistance. |
| Developments of new concepts designs | Wind resistant design | Study of the possibility of reducing wind load by reviewing natural wind fluctuation characteristics.<br>Development of flutter analysis. |
| | Seismic design | Setting two stages of design earthquake ground motions and studies of seismic design methods for each stage. |
| | Design of superstructures | Review of the safety balance of entire suspension bridge systems in order to achieve lower construction cost.<br>Studies of live load loading method that accounts for real conditions of motor vehicle traffic. |
| | Design of substructures | Studies of appropriate methods of evaluating ground bearing capacity and deformation. |
| Innovative execution methods | Reduction of construction cost | Studies of construction cost reductions by reviewing material standards and fabrication precision. |
| | Shortening of construction period | Studies of construction period reduction based on systematic overlapping of work steps.<br>Studies of work methods that increase the working days ratio under severe marine conditions. |

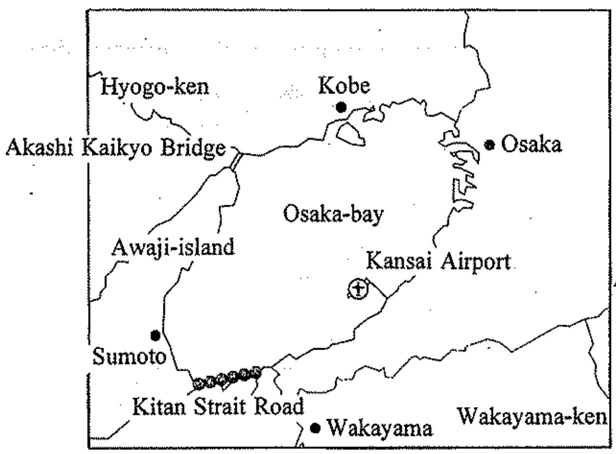
*Table 3.2 Effect of New Technological Developments (Case of Tokyo Bay Mouth Bridge)*

| Item | | | Trial design based on existing technologies | Trial design based on new technologies |
|---|---|---|---|---|
| Basic specifications | | Span lengths (m)<br>Cable interval (m)<br>Dead load (tf/m/Br) | 720 + 2,250 + 720<br>30.5<br>42.33 | 860 + 2,250 + 860<br>25.5<br>25.12 |
| Superstructures | Girder | Shape<br>Width × Height (m) | Truss<br>30.5 × 14.0 | Slotted box girder with open grating<br>32.0 × 4.0 |
| | Tower | Shape<br>Tower height (m)<br>Tower shaft interval (m) | Truss-type/reverse Y-type tower shaft<br>+324<br>30.5 ~ 52.0 | Rahmen-type / single tower shaft<br>+295<br>25.5 ~ 36.0 |
| | Cable | Allowable stress (kgf/mm2)<br>Diameter (cm) | 82<br>115 | 100<br>86 |
| Substructures | 1A<br>2P<br>3P<br>4A | Dimensions (m)<br>Dimensions (m)<br>Dimensions (m)<br>Dimensions (m) | 90 × 68<br>58 × 80<br>58 × 80<br>90 × 68 | 90 × 55<br>35 × 75<br>35 × 75<br>90 × 55 |
| Volume | Super-structures | Tower (tf)<br>Cable (tf)<br>Girder (tf)<br>Totals (tf) | 60,000 (1.00)<br>64,000 (1.00)<br>78,000 (1.00)<br>202,000 (1.00) | 37,000 (0.62)<br>35,000 (0.55)<br>58,000 (0.74)<br>130,000 (0.64) |
| | Concrete of substructures (m3) | | 1,448,000 (1.00) | 756,000 (0.52) |
| Approximate construction period (years) | | | 11 (1.00) | 6.5 (0.59) |
| Approximate construction cost | Superstructures<br>Substructures<br>Total | (100 million yen)<br>(100 million yen)<br>(100 million yen) | 2,420 (1.00)<br>1,730 (1.00)<br>4,150 (1.00) | 1,250 (0.52)<br>1,060 (0.61)<br>2,310 (0.56) |
| Remarks | | | | |




| Straits | Strait width (km) | Maximum water depth (m) | Maximum tidal current speed (m/s) | Maximum wave height (m) |
|---|---|---|---|---|
| Tokyo Bay Mouth | 12 | 80 | 1.0 | 8 |
| Ise Bay Mouth | 20 | 100 | 1.5 | 21 |
| Kitan Strait | 11 | 150 | 3.5 | 18 |
| Kanmon Strait | 2 | 20 | 1.5 | almost 0 |
| Hoyo Strait | 14 | 200 | 3.0 | 12 |
| Hayasaki Strait | 5 | 110 | 3.5 | 12 |
| Nagashima Strait | 2 | 70 | 4.0 | 18 |
| Akashi Strait | 4 | 100 | 4.5 | 10 |

*Figure 1.1 Major Trans-Strait Road Projects*



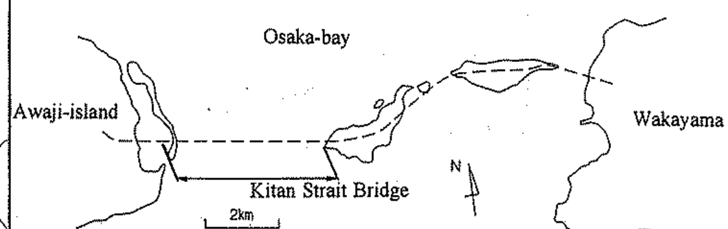




*Figure 2.1 Kitan Strait Road Route*

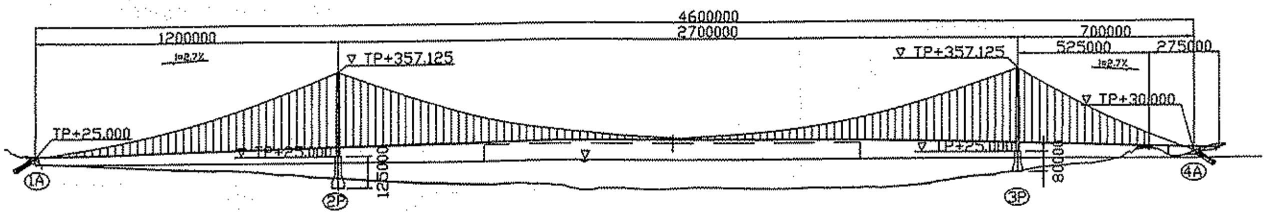



*Figure 2.2 Kitan Strait Bridge*

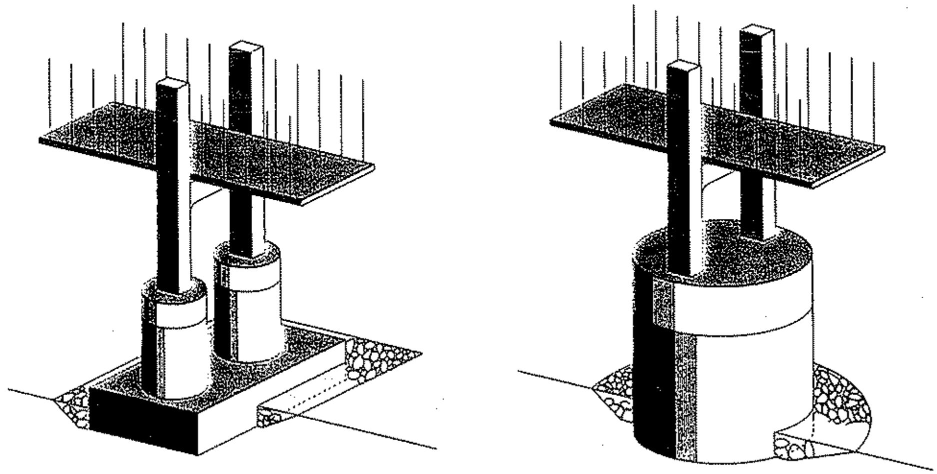


*Figure 3.1 Twin-Shaft Type Foundation (left) and Cylindrical Solid Foundation (right)*

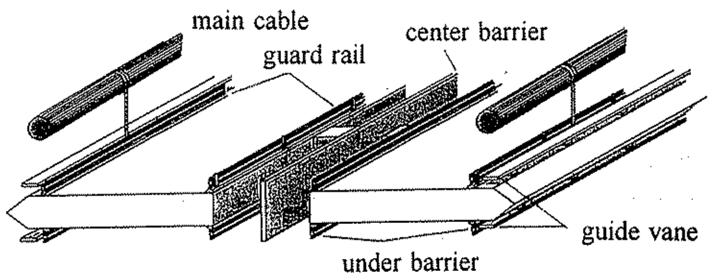



*Figure 4.1 Slotted Box Girder with Aerodynamic Appendages*

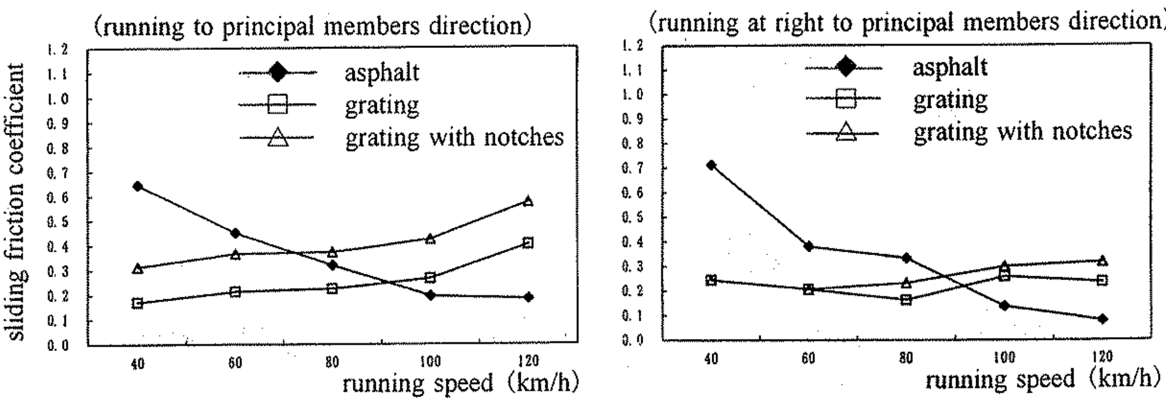



*Figure 4.2 Results of Skid Resistant Tests*

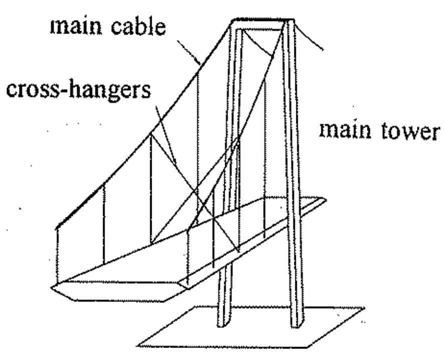



*Figure 4.3 Single Box Girder with Cross-Hangers*

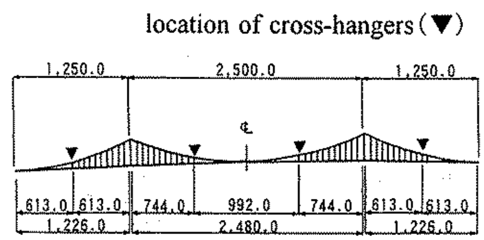



*Figure 4.4 Location of Cross-Hangers*

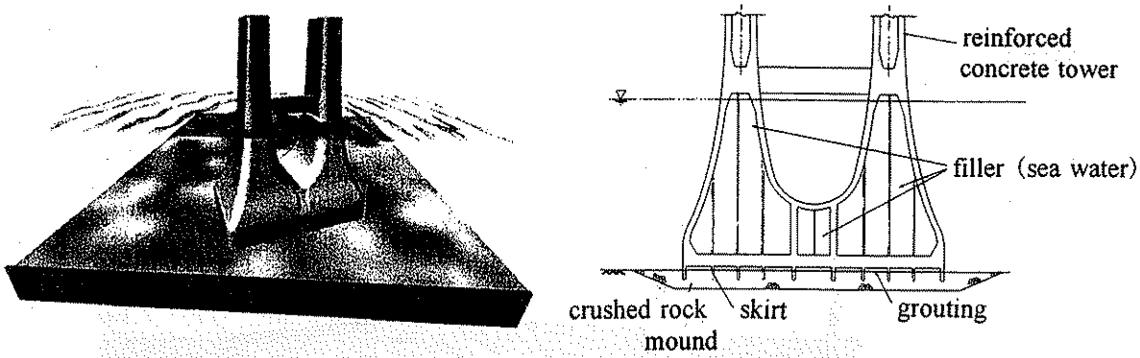



*Figure 4.5 Hybrid Caisson Foundation*

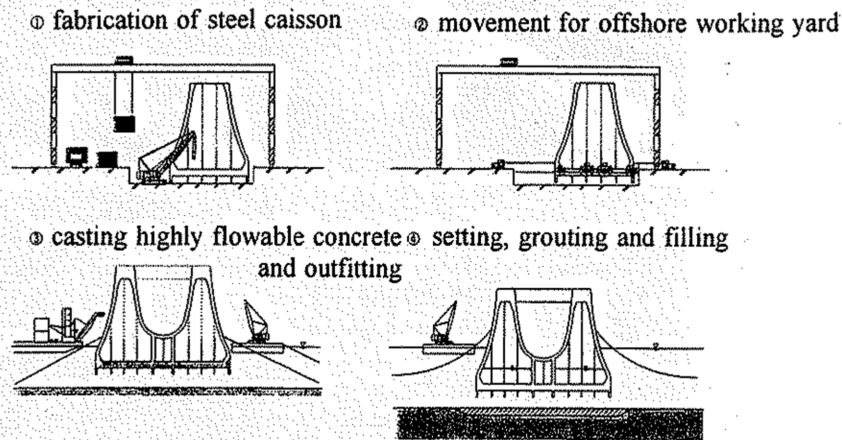



*Figure 4.6 Execution Procedure of Hybrid Caisson Foundation*

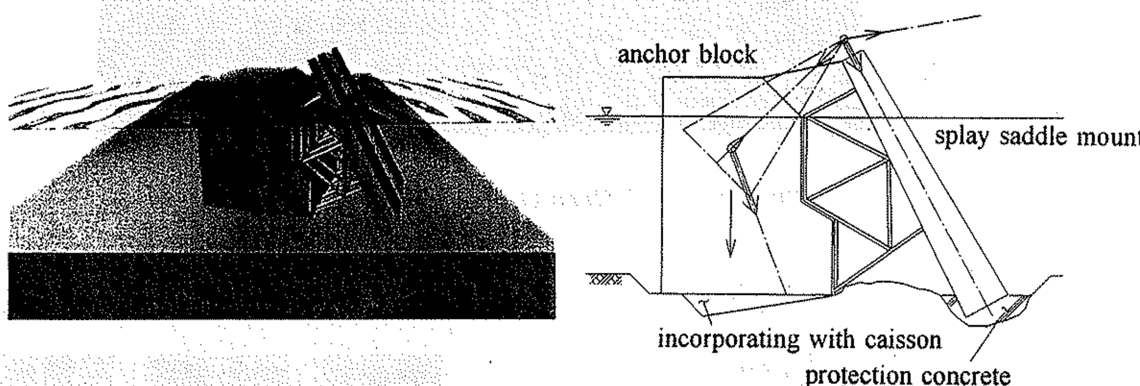



*Figure 4.7 Anchorage Separated of Splay Saddle Mount - Anchor Block*

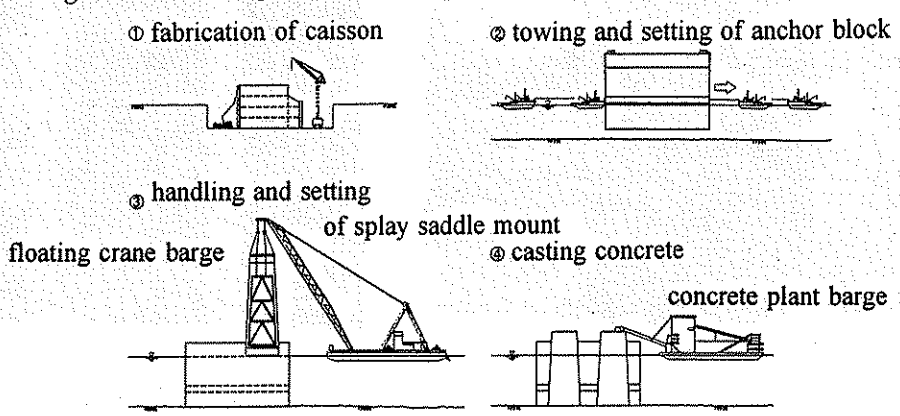
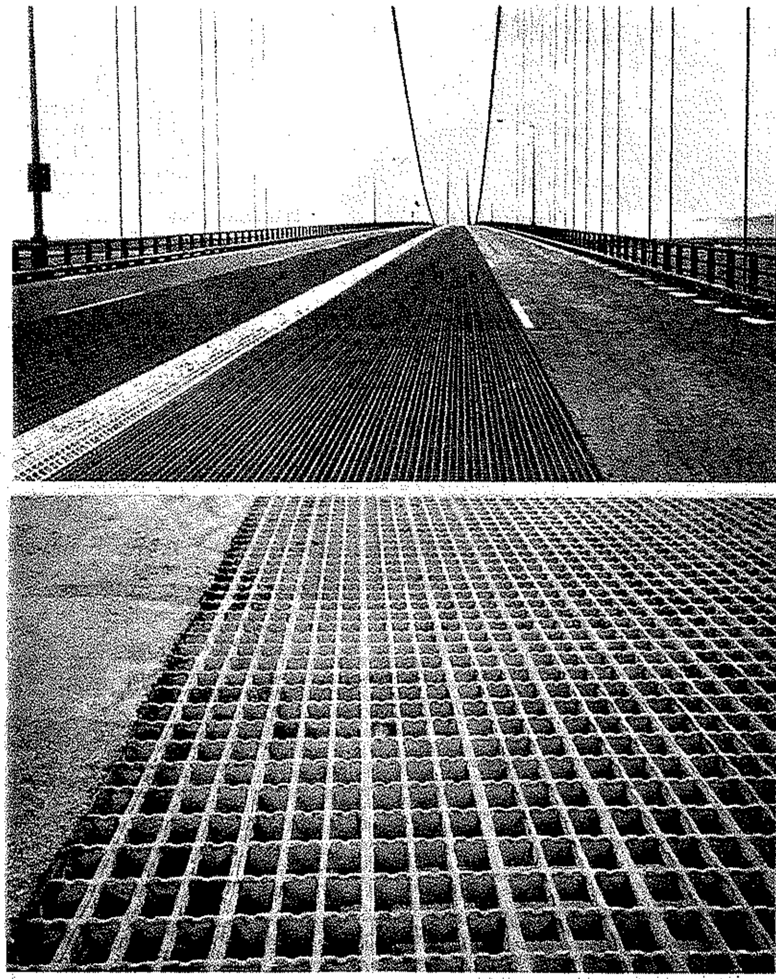
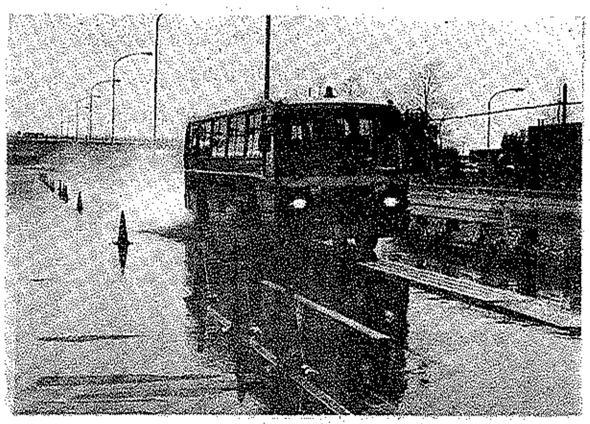


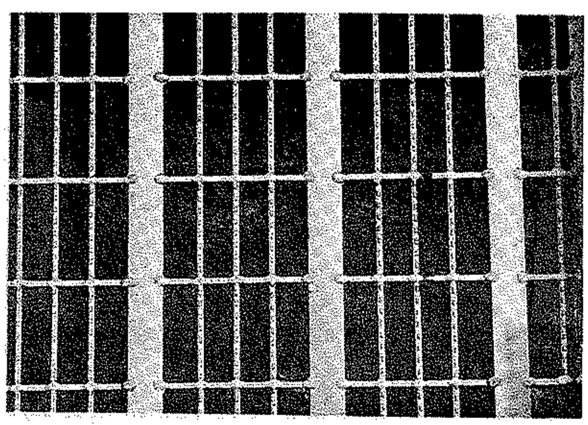

*Figure 4.8 Execution Procedure of Anchorage Separated of Splay Saddle Mount - Anchor Block*



*Photograph 4.1 Open Grating of the Mackinac Bridge*



*Photograph 4.2 Situation of Skid Resistant Tests*



*Photograph 4.3 Open Grating used Tests (with Notches)*