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Development of a Very Large Floating Structure

Tadashi TORII[*1] Hiroshi OHKUBO[*1]
Nobuyuki HAYASHI[*1] Kazumi MATSUOKA[*2]
Hisashi KANAI[*3]

Abstract

Very large floating structures (VLFS) are being developed as a totally new method for creating artificial land on the sea, hundreds to thousands of meters long, in the form of a floating body. Since the VLFS is quite different in structure from large ships like crude oil carriers, lots of technical aspects and problems have to be clarified and solved to construct VLFS a practical reality. One example is that, due to their [its] relatively small thickness in proportion to the huge length, VLFS should be considered as an elastic body as far as its behavior in waves is concerned. Accordingly, a numerical analysis method for clarifying its behavior was developed and measures for reducing its vertical displacement was studied. A mooring design was developed taking into consideration expected response behavior of the large mass floating body on waves when moored. Also were developed methods for joining float units sections into one large unit on the sea and ultra-long period anticorrosion measures. This paper focuses on the results Nippon Steel Corporation achieved regarding these and other aspects which it approached in relation to VLFS.

1. Introduction

Japan is an island country and its flat land areas are intensively utilized especially in urban regions where economic activity is highly concentrated. Looking for new land spaces available, land utilization has expanded to mountainous and coastal regions. The ocean space, on the other hand, has long been used for purposes such as fishery, exploration and production of mineral resources, transportation and recreation, and the coastal sea space has been used for expanding the land through reclaiming. Against this historical background, research and development of very large floating structures (VLFS, or ultra large floating marine structure) have recently been accelerated as a new form of utilization of the ocean space.

The VLFS is a new concept to construct facilities such as airports and materials handing terminals on the sea using floating structures as artificial grounds. (See **Fig.1**.) The first serious proposal of this concept was an alternative idea of a floating offshore airport for the Phase I of the Kansai New International Airport advanced by the Society of Naval Architects of Japan. At that time, the initial idea was to use a semi-submerged structure as the base structure and, then, a pontoon type floating structure was proposed for the Phase II by the Floating Structures Association of Japan aiming at cost reduction. However, these proposals did not finally realize due to various problems yet to be solved.

Ships are the most typical floating structures, and offshore oil production rigs, various types of buoys and floating piers are also other examples. As the largest floating structures ever built, we can count things such as a crude oil carrier 440 m long × 58.8 m wide × 29.8 m deep (Seawise Giant) and an offshore oil storage facility 397 m long × 82 m wide × 25.4 m deep (Shirashima Offshore Oil Stor-

*1 Civil Engineering & Marine Construction Division
*2 Steel Research Laboratories, Steel Structure Development Center
*3 Sagamihara Research & Development Division

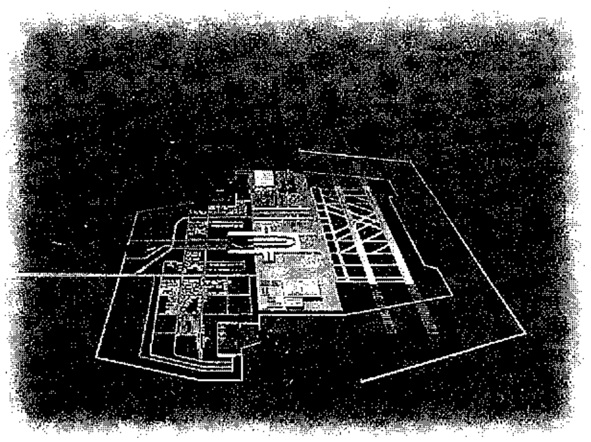


Fig.1 An example of VLFS (floating airport)

age). Because these large structures are built, generally, as an entire unit at a shipbuilding dockyard or a fabrication yard on the land, their dimension is automatically limited by the size of the fabrication facilities. By the VLFS, however, what is intended is a scale beyond fabrication as a single unit - several hundreds of meters or even several kilometers long, for instance. Although some of existing floating structures are made of concrete, they are predominantly made of steel due to the reasons of material strength, workability, durability, economy, and so on. For this reason their design and manufacturing technologies originated mainly from naval architecture.

When so large a structure as VLFS became concerned, however, matters heretofore unconsidered appeared as real problems and the lack of precedence as well. In this situation, for the purpose of solving these problems and carrying out real scale tests to verify proposed solutions, 17 steelmakers and shipbuilders of Japan formed the Technological Research Association of MEGA-FLOAT (TRAMF) in April 1995 and have since carried out joint researches under the framework of the organization.

This report describes outlines of the study results Nippon Steel obtained so far, independently or as a member of the joint researches of TRAMF, from the viewpoint of steel structure or marine construction, focusing on the following subjects regarding VLFS:

- Analysis of the elastic behavior of VLSF in waves and measures for suppressing displacement.
- Analysis of the mooring behavior of VLSF and the methods of mooring equipment design.
- Offshore construction methods.
- Corrosion protection methods of steel structures for a very long service life.

2. Elastic Behavior in Waves and Reduction of Displacement

2.1 Elastic Behavior in Waves

Because of its huge length in comparison with its thickness, the stiffness of VLFS is relatively small. Hence, it cannot be regarded as a rigid body, elastic deformation being predominant in its response to waves. Also, due to a large value of L (structure length)/λ (wave length), its movement in waves is small and so is suspected the stress resultant on its cross section. In consideration of the above characteristics of VLFS, an analysis of its behavior as an elastic body is indispensable to predict the operating ratio of the service facili ties to be constructed on it as well as economically design of VLFS.

2.1.1 Analysis of Response of Elastic Floating Body in Waves

In the conventional movement analysis dealing with rigid floating bodies, the movement of the bodies is calculated by calculating radiation potential (additional mass force, radiation damping force) and diffraction potential (wave exciting force) in consideration of boundary conditions and, then, obtaining hydrodynamic force by the Bernoulli's equation. In the case of a VLFS, in contrast, it is necessary to take into account flexibility of the entire body as an elastic body. For this reason, a calculation method was adopted whereby portions of the floating body in question is viewed discretely and radiation potential is calculated corresponding to each degree of freedom of the movement. In the present study, the boundary element method (BEM) was used for calculating hydrodynamic force and the finite element method (FEM) was used for calculating vertical motion of elastic floating body. Therefore, a wave response analysis method taking into consideration the interaction between fluid and floating structure (radiation force) was developed[1]. This new wave response analysis method made it possible to treat floating bodies of any given shape as elastic bodies.

2.1.2 Verification through Tests

Two-dimensional hydraulic model tests[2] were carried out to verify the analysis results, using a wave tank at Nippon Steel's Sagamihara Research & Engineering Center. (See **Fig.2**.) The model used was made of polyurethane foam (specific gravity 0.22, Young's modulus 1,051 kgf/cm^2) and its dimension was 10 m long × 0.5 m wide × 76 mm thick, corresponding to a 1,000 m long real VLFS on a scale of 1/100. The water depth was set at 1.1 m. The vertical displacement was measured with laser displacement meters.

Fig.3 shows the vertical displacements in the cases of wave period (T) of 0.8 sec. and 1.11 sec. as a comparison example of the values obtained from the tests with the same from the analysis. The longitudinal position (x) of the floating body is plotted on the axis of abscissa, and the quotient (dimensionless) of vertical displacement Z divided by wave height ζ_a on the axis of ordinate. Principal conclusions derived from the comparison are as follows:

1) Elastic response is predominant in the vertical movement of the floating body in waves and the response is highly dependent on the wave period.
2) The longer the wavelength becomes, the larger the vertical movement tends to be. The movement at both the ends is 2 - 3 times that at the other parts away from the ends.
3) The values obtained from the analysis calculations nearly conform to the measured values and, hence, the analysis method used is sufficiently useful as an engineering tool.

2.2 Reduction of Displacement in Waves

It was confirmed from the results of the numerical analysis and the tests that the displacement of VLFS in waves is predominantly of elastic response and that the vertical displacement at the ends are considerably larger than those at the other portions. Basic concept of the infrastructure facilities using VLFS is that breakwaters will re-

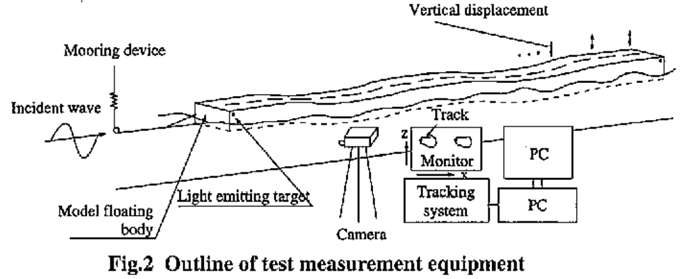


Fig.2 Outline of test measurement equipment

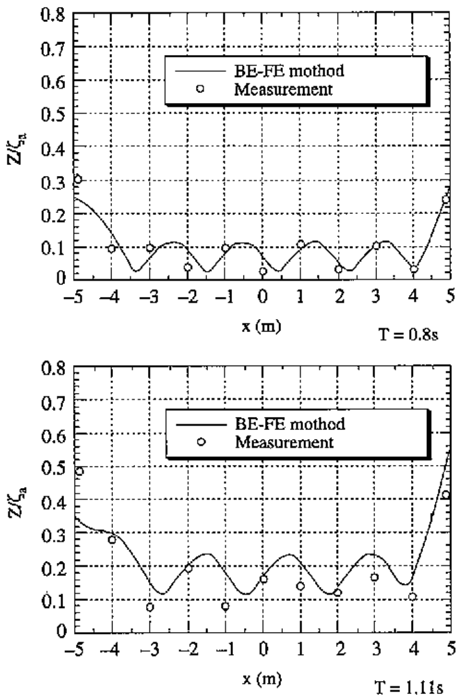


Fig.3 Comparison of distributions of vertical displacement response

duce its displacement. But there may be cases where the breakwaters have a large wave transmission coefficient due to environmental considerations, or the VLFS is to be constructed at a location facing the open sea. In such cases the above large displacement at the ends may pose a serious obstacle to the function of the service facilities to be constructed on the VLFS, or construction of the breakwaters may render the entire project uneconomical. Thus, for making VLFS economically competitive, it is desirable to develop a method to make the floating body capable of reducing the vertical displacement to an extent comparable to breakwaters.

2.2.1 Displacement Reduction Mechanism

Various methods to reduce the vertical displacement at the ends and, consequently, the center as well were proposed and examined. Two methods which proved effective in the hydraulic tests are described hereafter - installation of a submerged horizontal plate and that of a vertical plate at the wave-incident end of the floating body. (See **Fig.4**.) In the former method, a submerged horizontal plate is suspended, firmly fixed to an end of the floating body, and in the latter a submerged vertical wall is fixed at the end of the body.

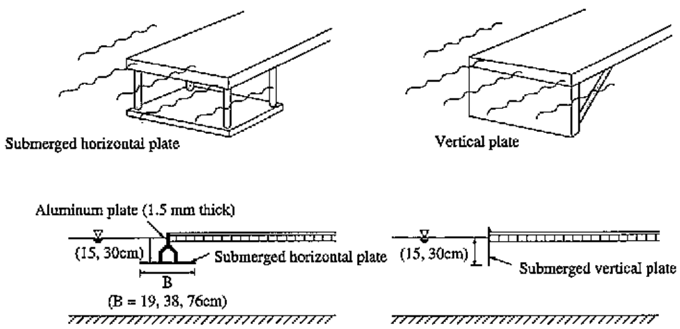


Fig.4 Mechanism for reducing vertical displacement

2.2.2 Study of Displacement Reduction Mechanism through Tests

A series of hydraulic tests were carried out[3] to confirm the effects of both the above methods. The model floating body used for the tests was made of hard PVC foam plate with low air content (specific gravity 0.7, Young's modulus 13,000 kgf/cm^2) 10 m long × 0.5 m wide × 15 mm thick, with polyurethane foam glued onto the lower surface for giving buoyancy. A real VLFS 1,000 m long was supposed on a scale of 1/100. The water depth for the tests was 1.1 m. The vertical displacement was measured with laser displacement meters. **Fig.5** shows a comparison of vertical displacement responses with and without the submerged horizontal plate (38 cm long, at the depths of 15 and 30 cm) in waves of 0.7 and 1.0 sec. periods. **Fig.6** shows the same with and without the vertical plate (plate heights of 15 and 30 cm in the water). In the figures, the axis of abscissa stands for the longitudinal position of the model, and the axis of ordinate the quotient (dimensionless) of the vertical displacement divided by wave height. The waves came from the left. The essence of the conclusions derived from the study is as follows:

1) Both the submerged horizontal plate and the vertical plate proved effective for reducing the displacement near the model ends. In some cases the displacement was reduced to 10 - 20%.
2) The displacement reduction effect was most conspicuous near the ends of the model, but a similar effect was observed also at the portions away from the ends.
3) Either mechanism proved effective. As a consequence, there arose a possibility that breakwaters are not required on comparatively calm waters.

The displacement reducing effect of the submerged horizontal plate varied depending on the length and depth of the plate. Added mass force when horizontal plate moves vertically is presently sus-

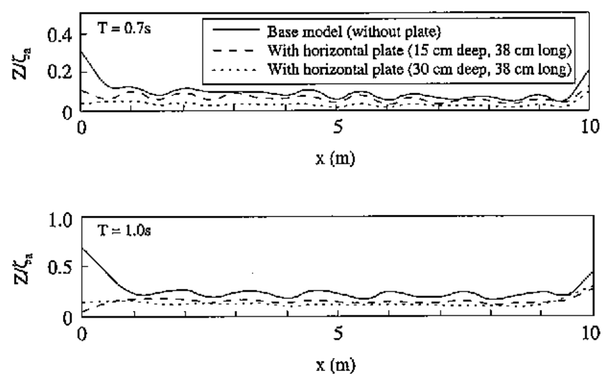


Fig.5 Vertical displacement distribution with submerged horizontal plate

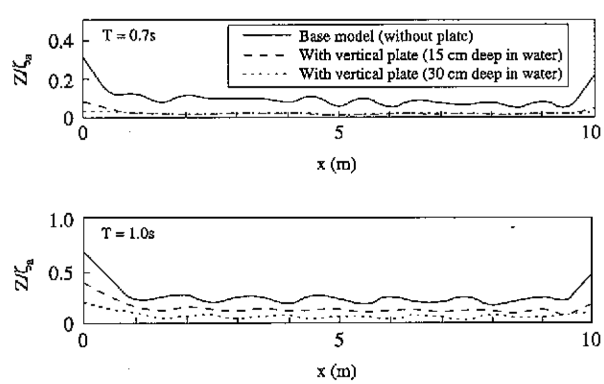


Fig.6 Vertical displacement distribution with vertical plate

pected to be one of the reasons for this. The effect of the vertical plate comes from the fact that a part of the incident waves is reflected and only a reduced portion of waves goes beneath the floating body. Since this effect is identical to that of curtain wall type breakwaters, the shorter the wave period, the larger the effect.

3. Mooring of VLFS

3.1 Characteristics of Mooring of VLFS

The proportion of the cost of mooring equipment of VLFS is comparatively small in the total construction cost. However, the mooring system is the very keystone of the concept of VLFS since it determines safety, the reliability and function of the floating structure through preventing it from drifting out of place under typhoons, and restricting its behavior in the horizontal plane in accordance with the required functions of the service facilities on it.

There are widely varied types of mooring equipment and the most adequate mooring method and equipment arrangement have to be selected in consideration of factors such as the natural period of the system in accordance with the size of the floating body, its object and the condition of the waters where it is constructed. The mooring system has to be so planned, in the context of an overall system, as to enhance the economy, safety and reliability of VLFS as compared with other alternatives. The aspects to be studied in the planning include: the relationship between required calmness of the sea obtainable by arrangement of breakwaters and mooring capacity limit; influence of the mooring system on access facilities; and its use for temporary mooring of sections (floating units) during their assembly work into the large structure.

System concepts, design examples and design methods are described in this section in relation with the mooring of VLFS.

3.2 Concept of Mooring System

There are examples of moored floating structures such as those of the offshore oil storage facilities at Shirashima and Kamigoto, some recreation facilities, tanker berths, and mooring wharves. In any of these, the size of the floating structures is several hundreds of meters and they are not "very large," nevertheless they are meaningful references of the mooring of floating structures for long periods under the offshore conditions. Methods such as a combination of dolphins with constant reaction fenders, use of chains and the like are employed for mooring these structures. Functions required of the mooring equipment for VLFS and selection of the mooring type are discussed hereafter.

3.2.1 Required Functions

Fig.7 is an example schematic arrangement of the mooring equipment for a floating airport of a 5-km scale. The floating structure is moored by multiple dolphins and the dolphins are arranged on one side of the floating structure in order to allow for the thermal expansion by solar radiation, which will amount to 1 m in the whole length of the structure. 50 dolphins are installed along one of the long sides and 20 along a short side. A dolphin connects to the floating body via constant reaction rubber fenders and a guide frame as shown in **Fig.8**.

Requirements of the mooring equipment for VLFS are as follows:

(1) To restrict VLFS's displacement in the horizontal plane against winds, waves and tides in accordance with the required functions of the service facilities on it.

(2) To provide sufficient bearing force against winds, waves and tides in emergency conditions and earthquakes and, at the same time, control the mooring force so that it may not become excessive.

(3) To absorb the relative displacement in the horizontal plane between the floating structure and the mooring equipment fixed to the bottom of the sea.

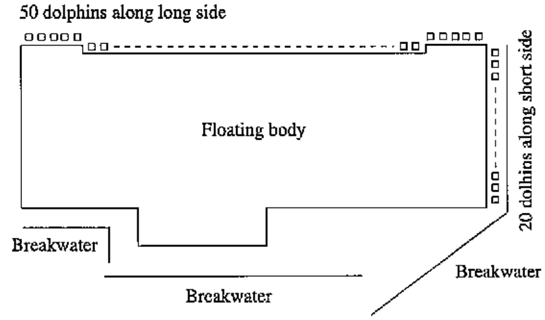


Fig.7 Schematic arrangement of mooring equipment

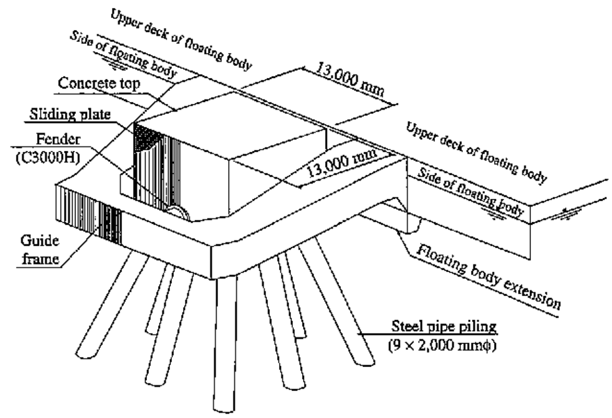


Fig.8 Connection mechanism of floating body with mooring dolphin

The relative displacement is caused by the expansion/contraction due to solar radiation and in-plane deformation (warpage) of the structure due to uneven solar radiation. The relative displacement of VLFS sometimes becomes so large that it leads to qualitative changes in the mooring method.

From the viewpoint of the restriction force of the mooring equipment on the floating body, the requirement of the above (1) is contradictory to (2) and (3). When a large restriction force is provided to suppress the displacement of the floating body, the mooring force caused by the displacement due to large waves, earthquakes or the in-plane deformation becomes very large and may make the mooring system uneconomical or practically unfeasible. On the contrary, if the restriction force is too small, the mooring force will be small and the system may be economical but the displacement of the floating body during its service will be so large that it may hinder the functions of the service facilities built on it. It is, therefore, important to select the most suitable mooring method in consideration of the maximum allowed displacement for the function of each service facility, the oceanographic conditions of the waters where it is installed and the amount of deformation of the floating body, and restrict it with adequate strength.

The following requirements have to be taken into consideration in addition to the above three: (4) to allow for the vertical movements of the floating body due to changes of tidal level and waves; (5) to absorb dimensional errors in the installation of the mooring facilities and fabrication of the floating structure; (6) to conform to height limits imposed on the facilities (air space regulations, etc); (7) to cope with tsunami; (8) installation workability; (9) durability;

Table 1 Tentative mooring designs for floating airport

	Model A	Model B	Model C
Breakwater	Provided on 2 sides	Provided on 3 sides	No
Design conditions of construction site	Significant wave height: $H_{1/3}$ = 2.2 m Significant wave period: $T_{1/3}$ = 4.8 s Wind speed: U_{10} = 27.5 m/s	Significant wave height: $H_{1/3}$ = 1.0 m Significant wave period: $T_{1/3}$ = 9.6 s Wind speed: U_{10} = 50 m/s	Significant wave height: $H_{1/3}$ = 4.6 m Significant wave period: $T_{1/3}$ = 9.6 s Wind speed: U_{10} = 50 m/s
Water depth	20 m	22 m	20 m
Structure of floating body (length × width × depth × draft)	Pontoon (4,770 m × 1,710 m × 7 m × 1.5 m)	Pontoon (4,560 m × 1,000 m × 4.5 m × 0.72 m)	Semi-submerged (5,000 m × 840 m)
Structure of dolphin	50 units on long side 20 units on short side Design load: 1,018 tf/unit	108 units on long side 11 units on short side Design load: 700 tf/unit	22 units on long side 15 units on short side Design load: 2,000 tf/unit
Connection mechanism	Guide frame	Guide frame	Dolphin link
Fender	Constant reaction force type fender Height 3 m, 2 pieces/dolphin	Teflon	Constant reaction force type fender Height 2.25 m, 16 pieces/dolphin
Governing load	Wave load (slow-drift wave excitation load)	Fluctuating wind load, Seismic load	Wave load
Reference	Report of TRAMF	Floating Offshore Airport (edited by Marine Float Promotion Organization)	An Example Assessment of Technologies for Ultra-large Marine Structures. Journal of Soc. Naval Arch. of Jpn. Nos.638 - 652

(10) maintainability; (11) cost performance; and so forth.

3.2.2 Selection of Mooring Method

Three tentative mooring designs for a floating airport of a 5-km scale are listed in **Table 1**. The size of the floating body and the requirements from the function of the airport facilities to restrict the movements of the floating body impose very demanding conditions on the mooring facilities. All the three design alternatives consider construction of the floating airport at a bay about 20 m deep, and all of them adopt the multi-point dolphin mooring method. Calmness of the waters is different whether or not breakwaters are provided and how they are arranged. The connection mechanism of the dolphin with the floating body and the type of the fenders are selected in accordance with the different design conditions, and consequently different governing loads are assumed in compliance with factors such as the natural period of the mooring system.

3.3 Design Method

In the first stage of the mooring system design, that is, in the basic study, primary selections are made regarding the mooring method, the number of the mooring equipment units, their arrangement, fender type, and so on in accordance with the environmental conditions and required functions. Then, simulations of the in-plane behavior of the floating structure are carried out in view of various loading conditions. Based on the results of the simulations, the arrangement and the number of the equipment are adjusted so that the calculated movement of the floating body and the mooring force fall within the permitted ranges. The dolphins and other mooring facilities are designed on the basis of the definitive mooring force thus defined.

The above design procedures are fundamentally identical to those for the conventional mooring systems, but, due to the difference in the size of the floating structure, attention should be paid to the following points:

(1) Because of the huge mass of the floating body, natural period of the combined mooring system composed of the floating body and the mooring equipment is as long as tens of seconds. For this reason, the system may resonate with fluctuating loads having long periods such as slow-drift wave excitation loads, fluctuating winds and long period waves. The study of long period resonance has, therefore, to cover a wide variety of loads. With regards to earthquakes, because of the long natural period of the mooring system the floating body becomes base-isolated and will not shake, but seismic loads may become the governing load on the mooring equipment and, for this reason, structural studies should cover interactive effects between the floating body and the mooring facilities.

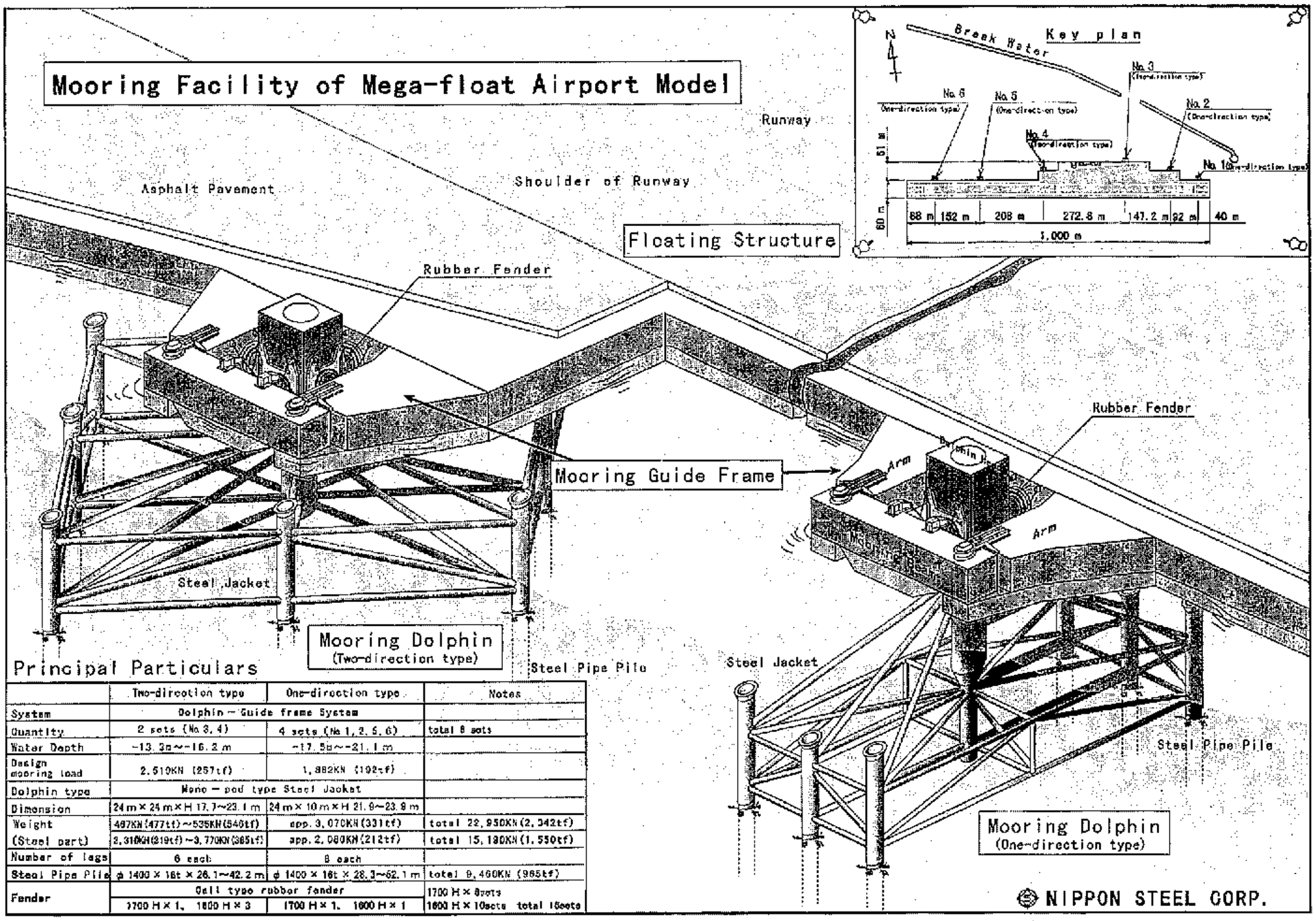
(2) Since slow-drift wave excitation loads often becomes the governing load because the natural period of the mooring system for VLFS is as long as several tens of seconds, the calculation of wave drifting force becomes essential. The value of the wave drifting force coefficient is expected to decrease due to elastic deformation of the floating body. Further, because of its huge size, VLFS will have a significant influence on the wave field. In calculating the hydrodynamic force, therefore, VLFS and all the surrounding facilities, such as breakwaters and revetments, should be viewed as one system in the analysis.

(3) Because of the size of the floating structure, when calculating wind loads it is necessary to take into account three-dimensional fluctuation of the loads. With regards to the fluctuating wind forces due to gusts, a load cancellation effect is expected there to be due to three-dimensional correlation.

(4) The solar radiation causes large expansion/contraction and in-plane deformation of VLFS.

3.4 Mooring Equipment for MEGA-FLOAT Phase-II Floating Airport Model

In the Phase II joint research[4] of TRAMF (in fiscal 1998 - 2000), a floating airport model capable of accommodating airplane take-off and landing tests was designed and constructed at a site off Yokosuka in the southwestern part of the Tokyo Bay. (See **Fig.9**.) The steel pontoon type floating body was the largest floating structure ever built in the world - 1,000 m long × 121 m wide. The mooring equipment consists of 6 mooring dolphins, guide frames for connecting the floating body with the dolphins and fenders. Design work of the



	Two-direction type	One-direction type	Notes
System	Dolphin − Guide frame System		
Quantity	2 sets (No 3, 4)	4 sets (No 1, 2, 5, 6)	total 6 sets
Water Depth	−13.3m～−16.2 m	−17.5m～−21.1 m	
Design mooring load	2,510KN (257tf)	1,882KN (192tf)	
Dolphin type	Mono − pod type Steel Jacket		
Dimension	24 m × 24 m × H 17.7～23.1 m	24 m × 10 m × H 21.9～23.9 m	
Weight	467KN (477tf)～535KN (546tf)	app. 3,070KN (331tf)	total 22,950KN (2,342tf)
(Steel part)	3,310KN (319tf)～3,770KN (385tf)	app. 2,080KN (212tf)	total 15,190KN (1,550tf)
Number of legs	6 each	8 each	
Steel Pipe Pile	φ 1400 × 16t × 26.1～42.2 m	φ 1400 × 16t × 28.3～62.1 m	total 9,460KN (965tf)
Fender	Cell type rubber fender		1700 H × 6sets
	1700 H × 1, 1600 H × 3	1700 H × 1, 1600 H × 1	1600 H × 10sets total 16sets

Fig.9 Outline of MEGA-FLOAT demonstration model for floating airport and mooring equipment

mooring equipment included a system design phase for the entire mooring system and an equipment design phase for the mechanism and structure of individual components. (See **Fig.10**.)

3.4.1 Design of Mooring System

First, the following conditions of the floating body and the mooring facilities were set forth: natural environmental conditions from the construction period to the post-completion period (site conditions, surrounding topography and soil conditions, water depth, wave, wind, temperature, etc.); operation conditions (obstruction-limited surface of the airport facility, permissible displacement, etc.); and

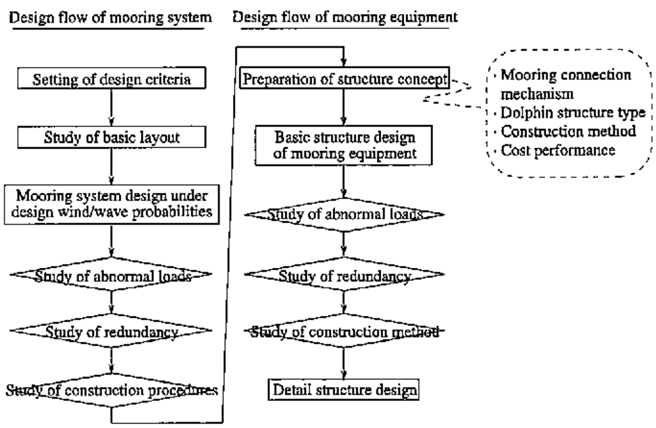


Fig.10 Design procedures of mooring equipment

design criteria such as the maximum allowable values of strength and displacement and so on corresponding to the above conditions. Three different oceanographic conditions were considered: a normal (operating) condition, a storm condition (encounter probability 0.2); and an abnormal condition (extreme storm conditions - encounter probability 0.02, earthquakes and tsunami). Additionally, two more conditions were included as special cases: an accident condition where one of the dolphins is missing; and esch case during the construction phase where floating units are moored and jointed one by one. Studies were carried out for working out an optimum arrangement and the specifications of the mooring facilities under the above conditions. As a result, an arrangement of six mooring units was selected and, among the six, two at the center were designed for two-directional mooring (longitudinal and transverse) in order to cope mainly with the surge and the sway, and the other four (two at each side) were designed for one-directional mooring (transverse) to restrict, mainly, the yaw and the sway.

3.4.2 Mooring Simulation

A dynamic response analysis was carried out to clarify the behaviors of the floating body under fluctuating external forces. The object of the analysis of the mooring system for the VLFS is to clarify the horizontal motion, which is little affected by the elasticity of the floating body. For this reason, a motion equation which dealt with the motion as those of a rigid body having six degrees of freedom was used in the analysis for the evaluation of the horizontal responses having three degrees of freedom (surge, sway and yaw). The radiation hydrodynamic force (added mass force, radiation damping force) and the diffraction hydrodynamic force (wave exciting force) in the motion equation were calculated using a hybrid method[5)] of three-dimensional velocity potential continuation method and the boundary element method. The wave drifting force was calculated based on the calculation result of a corresponding rectangular elastic body model in consideration of the influence of the elasticity of the floating body. With regards to the restoring force characteristics of the fenders, fluctuating factors were taken into consideration such as non-linear properties, hysteresis and temperature influence. The numerical calculation yielded time domain responses of the floating body to fluctuating external forces in the motion equation. The calculation was made at intervals of one second for actual period of 6,000 seconds. This corresponds to about 1,000 waves with a design significant wave period of 5.8 sec. The maximum value of response was assumed to be equivalent to the expected value with a probability of 1/1,000. Calculations were made regarding 20 cases of irregular waves having different phases, and safety was judged through statistic operations of each of the maximum responses.

3.4.3 Design of Mooring Equipment

The dolphin-guide frame method was adopted as the mooring type since it secures the horizontal position of the floating body while allowing for its vertical movements in tides and waves. Constant-reaction type rubber cell fenders were placed between the dolphin and the guide frame. The dolphins were designed as mono-pod type dolphins consisting of a mooring column, connecting to the runway floating body having a minimum protrusion above the water surface for avoiding interference with the obstruction-limited surface of the airport, and a steel jacket type substructure supporting the column. (See Fig.9.) Dimensions of each of the components were decided not to cause release and collision of the floating body in consideration of the factors such as water level fluctuation due to tides and tsunami, the elastic response of the floating body in waves, thermal deformations and so forth. In the structural strength study of the components, the components were selected to meet the load conditions, the allowable stress and so on set forth for widely varied conditions. Further, a sufficient redundancy was given in consideration of accident cases such as where one of the structural components is missing. The ultimate strength was calculated by a pushover analysis, by means of static elasto-plastic analysis, to confirm the redundancy. In consideration of the above conditions, Nippon Steel proposed a low-head restriction type mooring system for an airport application and this was finally adopted.

3.5 Summary

Conventional types and design methods of the mooring systems of existing floating structures can be applied to the design of the mooring facilities for VLFS. However, as stated above, because of its large size, VLFS imposes new technical problems to overcome such as:

(1) A wider frequency range of fluctuating loads has to be studied because the natural period of the mooring system is long.
(2) In calculating the hydrodynamic force including the wave exciting force, the VLFS and all the surrounding facilities, such as breakwaters and revetments, should be viewed as one system in the analysis.
(3) Amount of deformation caused by the solar radiation is far greater than what has been experienced so far.

Further, in view of the significance of the facilities to be installed on the structure, it was necessary to accurately predict the behavior of the floating body against abnormal external forces exceeding design loads. Safety of the system was confirmed through analyses taking toughness of the dolphins into account. Various analysis tools were worked out through the joint research activities along with TRAMF[5-7)] and, thus, a condition was established for proposing the mooring systems for VLFS with sufficient safety and reliability.

For the mooring system of the Phase II model floating airport, the authors proposed a reliable structure combining existing types of hardware backed by proven performance through actual applications. There are rooms for enhancing the performance and economy of the mooring system through application of technologies to be developed in the future. It is believed to be important, in the future proposals related to VLFS, to study the mooring system not as an element separate from the others but to view it in the context of one integral system including the floating structure, breakwaters and access facilities. In this way, a safer and more economical type of mooring system from among widely varied alternatives will be chosen.

4. Offshore Construction Technologies

Conventional floating structures are fabricated at shipbuilding docks or structure fabrication yards as one complete unit and then launched to the sea by introducing water into the dock or using cranes, floating docks or semi-submerged barges. However, when a structure is so large that it exceeds the size of existing fabrication facilities, its fabrication on the land as one unit becomes uneconomical, and when the structure is several kilometers large, the idea is unrealistic. Hence, the proposed construction method of VLFS is that sections of the floating body (floating units) - each 100 to 300 m large - are made at fabrication facilities on the land, transported to the site, and then jointed into one large unit. (See **Fig.11**.)

Joining of two bodies floating on the water has only been implemented on calm waters or in a small scale such as enlargement work of ships (jumboizing) and connected pontoons. On the wavy open

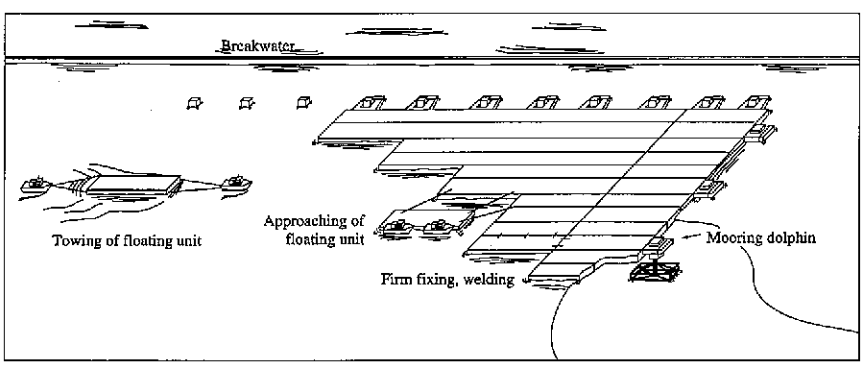


Fig.11 Conceptual illustration of VLFS construction

sea, there have been no precedents comparable to what is intended in this report except for the MEGA-FLOAT joint research, the only other past references being the joints between a pusher barge and a push boat, on a far smaller scale.

There are the following problems to overcome in the construction of VLFS especially with regards to the fastening of two floating units:

(1) Suppression and restriction of relative displacement between two units until completion of the fastening work.

(2) Fastening method of the units.

4.1 Mooring, Approaching and Fastening of Floating Units (Towing, Positioning and Displacement Restriction)

The floating structure is expanded through jointing together, one by one, the floating units which were prefabricated at fabrication yards, towed to the construction site and moored there. Various methods were proposed and verified in the joint research of TRAMF and on other occasions for joining new floating units onto the already completed portion of the floating body. **Fig.12** shows an example of basic construction procedures. A unit is brought horizontally near the already joined portion of the floating body, and after drawing close to it (primary matching), relative positioning and restriction of relative movements are gradually done (secondary matching) to firmly fix them to each other so that they can be finally welded together. Various jigs are employed for the work, such as displacement suppressing devices and positioning stoppers.

4.2 Load Estimation Method for Fixing and Fastening of Floating Units

In planning the site assembly work such as choice of jigs, estimation of operating ratio in the actual connection work and so forth, it is important to accurately estimate the loads on the joints between the units at each stage of the connection work.

The governing load during the connection work is the fluctuating load caused by waves and the most practical method for estimating it is to analyze the displacement of the connected floating body in waves assuming that it is a rigid body. Because of the thin shape of the object floating body, however, it was feared that the elastic behavior would become pronounced and an intrinsic deformation mode of higher-order with large curvature would be excited, causing unexpectedly strong loads on the joints. It is also important to understand suitable restriction strength required at each of the connection work stages and influence of the oceanographic conditions on the characteristics of the load on the joints.

Photo 1 shows an overview of a two-dimensional water tank test[8] carried out as a fundamental study of behaviors of the floating units during the connection work. For simulating real units, 200 m long each, two plastic models of a 1/25 scale having the same flexural rigidity were prepared and fastened together for testing their movements in waves.

Fig.13 shows the amplitudes and phases of longitudinal distribution of the vertical displacement measured at different points of the model. It is clearly seen here that the elastic deformation of the floating body is predominant. **Fig.14** shows the longitudinal distribution of shearing force calculated through splitting the displacement distribution obtained into elastic deformation modes. As is seen here, there are four peaks of amplified shearing force. As none of the peaks coincided with the joint of the model under the test condition, the load on the joint was not amplified, but a great amount of load may be imposed on it depending on where the peaks are. The above test result shows that the influence of the elastic deformation of the floating body plays an important role in the load estimation of the joints.

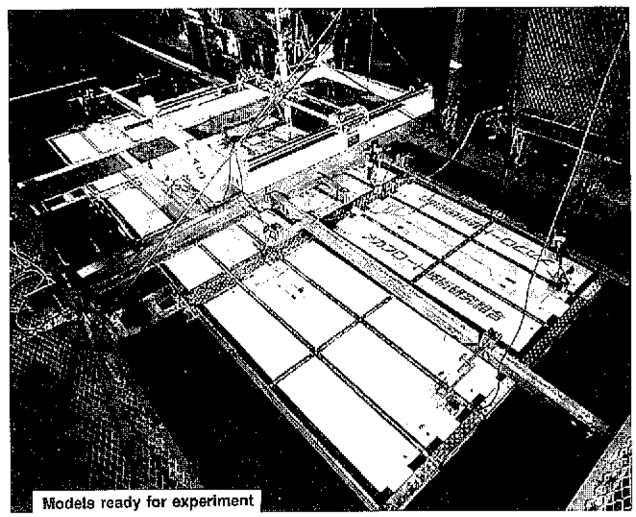


Photo 1 Overview of water tank test

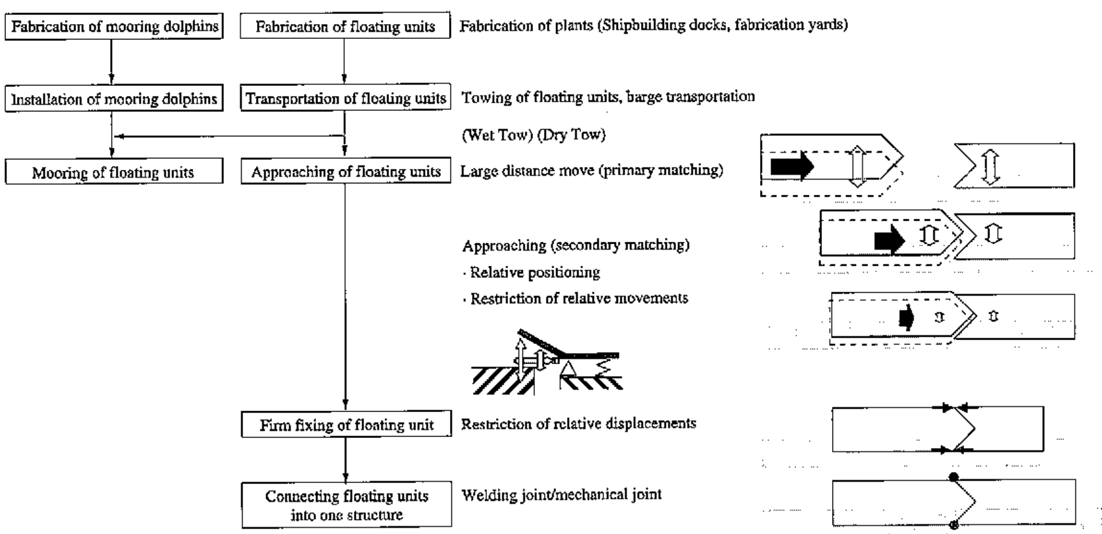
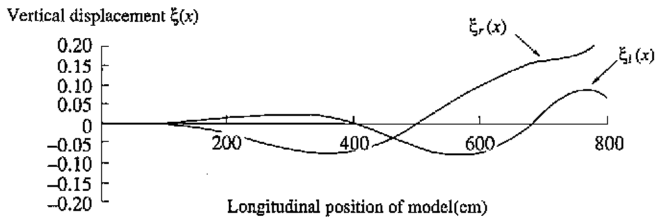


Fig.12 Construction procedures of VLFS



$\xi(x)e^{i\omega t} = Re[\xi(x)e^{i\omega t}] + i\,Im[\xi(x)e^{i\omega t}] = (\xi_r(x) + i\xi_i(x))e^{i\omega t}$

Re[ ] : real part Im[ ]: imaginary part

ω: Circumferential wave number of wave (rad/s)

Fig.13 Longitudinal displacement distribution during connection work of floating units

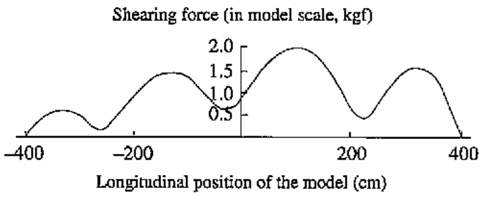


Fig.14 Longitudinal distribution of shearing force

In addition to the above test, a wave response analysis[9] was carried out taking into account the load measurements and the influence of hydrodynamic elasticity obtained during the connection work of the floating units of the MEGA-FLOAT Phase I model. Thanks to these, the load estimation of the joints has been made so accurate that it is now applicable to the real-size structures.

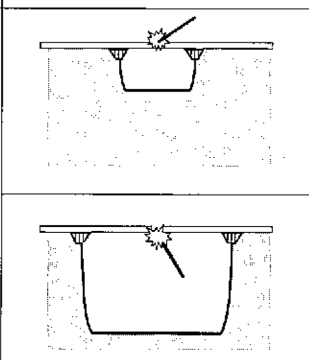
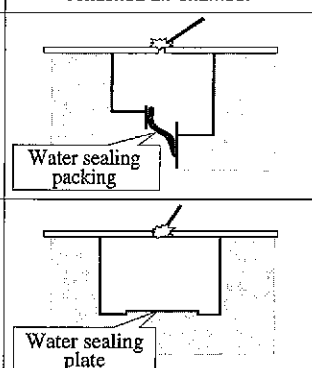
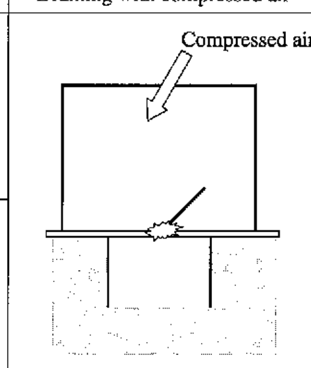
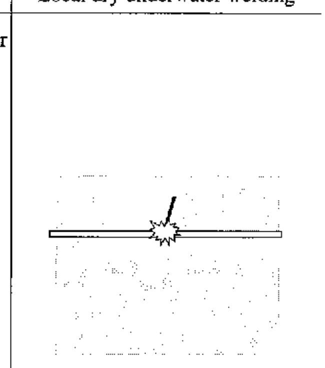
4.3 Offshore Connection of Floating Units

The floating units can be connected either by welding or mechanical joints. In the former method, wherein structural members (outer shells and internal members) of both the units are continuously welded together at their respective connection ends, there is no structural discontinuity and stress is well distributed, while water-tightness of the welded joints and high reliability of the welding work are required. In the latter, wherein the units are connected together by means of joint pieces having a coupling function and sufficient strength, the mechanical connection work takes a comparatively short time and a detachable mechanism can be employed. On the other hand, although the units are unified macroscopically, partial discontinuity remains in the members, and there may be displacement between the joint faces, and loads may concentrate on the joint pieces. For this reason, the mechanical connection is effective only for applications where the above drawbacks are acceptable and detachability is required.

The welding connection is more suitable for constructing integrated floating structures intended for a long service life like floating airports and it is more economical, as well. The welding work beneath the water level (underwater welding), however, is a problem in the offshore construction work. There are two kinds of underwater welding: the dry underwater welding whereby a welding atmosphere is formed around the joint by removing water from the joint vicinity; and the wet underwater welding whereby the welding work itself is done in the water. (See **Table 2.**) The wet method requires divers and special sheathed welding rods. For obtaining high quality welded joints by this method, highly skilled welders and helpers are indispensable and thus the method may not be economical when a great amount of welding has to be done like the construction work of VLFS. It is thus effective only when it is difficult to remove the water, the welding position is deep in the water.

Conventional welding methods, for which an ample welding manpower is available, are applicable to the dry method and thus it is more effective for welding a great amount of joints. For this, water removal measures are necessary for economically forming the welding atmosphere around the floating body shells under the water level, and the methods illustrated in Table 2 have been proposed[5-7] for the purpose. Each of them has its characteristics in relation to the use or otherwise of insert plates and/or backing metals and is applicable in accordance with specific condition of the joints. In the method using the water-sealing packing, the connecting portions of both the floating units below the water level are sealed watertight by the rubber packing immediately upon matching and fixing of the two units and then welding atmosphere is established by pumping out the water from the space inside the packing. This method was developed by

Table 2 Welding methods for connecting floating structures below water level

Classification	Dry underwater welding			Wet underwater welding
	External chamber	Attached air chamber	Draining with compressed air	Local dry underwater welding
Conceptual illustration				
Outline of work method	Water is sealed by packing at contact face with bottom shell and pumped out. Small chamber is for welding work from inside floating body, large chamber for welding work inside itself.	After matching floating units, small water-sealed chamber is formed outside bottom shell, water being pumped out. By packing method, chamber is formed immediately upon final matching and draining.	Wall plates are welded to bottom shells on both sides of joint to form air chambers. Water drained with air, pressurized from inside floating body.	Bottom shell welded in direct contact with water. Automatic welders used for local dry underwater welding.

Nippon Steel as a quick working method and its effectiveness was verified in the MEGA-FLOAT joint research. Use of automatic welding machines for the local dry underwater welding was developed in the joint research[5-7], and this is an effective means where suitable work conditions are provided.

5. Technologies for Long Service Life

A service life of 100 years is expected of VLFS as bases for infrastructure facilities intended for permanent use. Hence, a great deal of importance is placed on technologies to give durability to the structure. The technologies listed in **Table 3** were developed through the joint research with TRAMF for rendering VLFS durable for a long period. Outlines of principal technologies Nippon Steel implemented are described below.

5.1 Study of Optimum Corrosion Protection System

Once completed, VLFS cannot be returned to a shipbuilding dock for maintenance. For this reason, a service life basically of 100 years was envisaged in the study of its corrosion protection specifications, which are shown in **Fig.15**. Its characteristic features include: use of titanium cladding steel plates at the splash zone; combination of paint coating and the sacrificial anode method applied to the bottom; and dehumidifying method used for the void sections. Titanium was chosen for protecting the splash zone because it easily guarantees a good corrosion protection for a long period in the natural environment and its performance has been proven through its application to the piers of the Trans-Tokyo Bay Roadway Steel Bridge. The cathodic corrosion protection method using anodes durable for 100 years and having proven protection performance in the sea water was chosen for the bottom and the internal ballast tanks of the floating body. A dehumidifying agent was used for corrosion protection of the void portions because of cost advantage in view of the high cost expected of the painting and its maintenance of all the wide surfaces of the void portions. The same basic ideas were applied to the corrosion protection specifications of the mooring system.

5.2 Study of Applicability of New Materials

Problems involved in the application of corrosion protection materials to the splash zone were examined in this study. As the result of a comparative study of corrosion protection materials with JIS SUS316 and Alloy625, titanium was selected as the subject of further studies for the reasons explained above. Then the following problems were studied in relation to its application to the floating bodies: (1) lining work tests for verifying workability in the offshore environment; (2) development of an automatic welder for the offshore use; and (3) tests of offshore repair work methods. **Photo 2** shows an offshore lining work test and **Fig.16** the developed welder. For stable and quick welding work of titanium under the offshore working conditions, double-torch plasma welding method was introduced for the automatic welder. In the tests of offshore repair work, an artificial defect was created on a titanium-cladding plate previ-

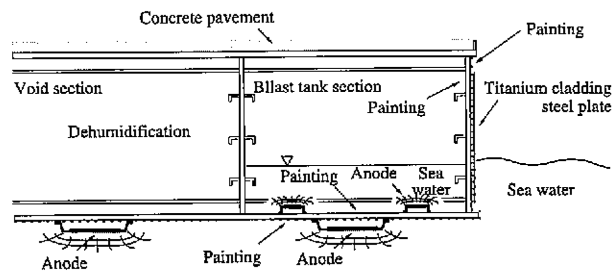


Fig.15 Corrosion protection system of MEGA-FLOAT

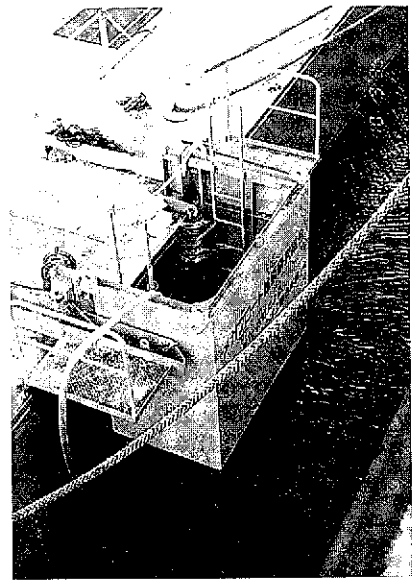


Photo 2 Offshore lining work test for demonstration

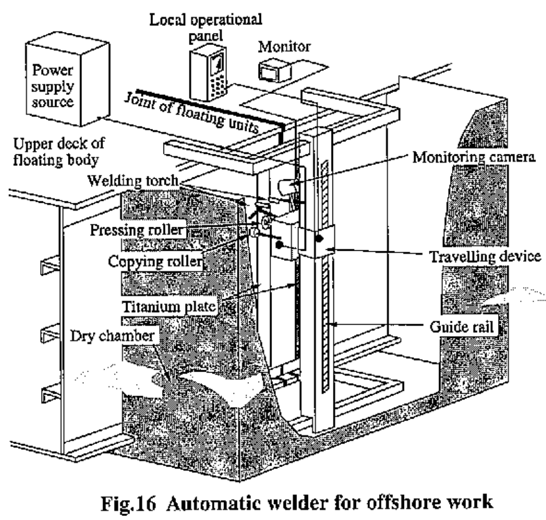


Fig.16 Automatic welder for offshore work

Table 3 Joint research items on long durability technologies and Nippon Steel's related technologies

Research subject	Joint research items	Nippon Steel's related technologies
1. Study of optimum corrosion protection system	(1) Study of specifications of corrosion protection system durable for 100 years* a) Floating structure b) Mooring structure	
2. Study of applicability of new materials	(1) Technology development for use of titanium and stainless steel materials for protection of splash zone of floating body*	(1) Development of corrosion protection methods using titanium
3. Development of long term monitoring technology	(1) Technology development for monitoring electric potential (2) Technology development for underwater monitoring	
4. Development of underwater repair technology	(1) Technology development for repair of floating body bottom shell	

* Nippon Steel was responsible for the item.

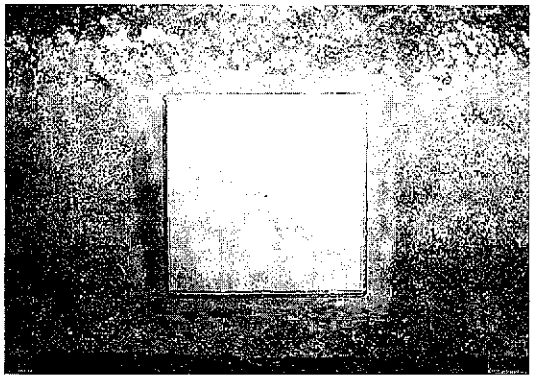


Photo 3 Test work of offshore repair for demonstration

ously welded onto the floating body and a titanium plate patch was welded to cover the defect. (See **Photo 3.**) It was confirmed through these tests that the corrosion resistant metal materials could be welded satisfactorily when a dry chamber is provided to create an atmospheric condition.

5.3 Corrosion Protection Methods Using Titanium

Nippon Steel has long noticed effectiveness of titanium for long-lasting corrosion protection of steel structures and developed a variety of titanium application technologies for marine structures on its own initiative after the application of titanium cladding steel plates to the Trans-Tokyo Bay Bridge. Some examples are described hereafter.

5.3.1 Steel Pipe Pilings with Titanium Lining

Steel pipe pilings are commonly used for supporting marine structures such as large-scale piers, and for the mooring structures for VLFS as well. A long-lasting corrosion protection is required of the pipe pilings in order to secure a long service life of the facility supported by them. In this context, Nippon Steel developed a steel pipe piling product with a thin titanium plate lining welded at the manufacturing plant for economically realizing a long-lasting corrosion protection. (See **Fig.17.**) A thin gauge titanium plate is used as the primary protection layer and an organic resin coating as the secondary protection layer. Good workability was confirmed through driving trials using prototype pilings having the above specifications, (See **Photo 4.**) and the product has been applied to actual construction projects as well. A method for providing corrosion protection at the site, named TP (Titanium lining pipe) method, was also developed, whereby a thin titanium plate is put around a steel pipe piling at the site and the seam is joined with a sleeve joint. (See **Fig.18.**) This method has accumulated many application references.

5.3.2 Corrosion Protection by Thin Titanium Plate Lining for Steel Structures

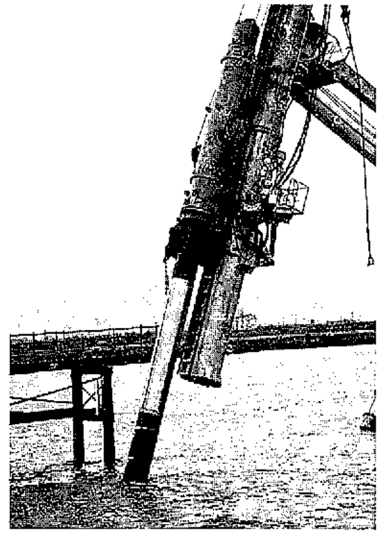


Photo 4 Trial driving of steel pipe piling with titanium lining

It is a common practice to use painting system for protecting floating structures against corrosion in the portions above splash zone. There is a concern, however, that the costs for the rehabilitation work would amount to a considerable figure when a service life of 100 years is supposed. It is, hence, desirable to use a long-lasting corrosion protection method such as the one considered for the splash zone. For this reason, Nippon Steel developed a low-cost corrosion protection method using thin titanium plates for lining steel structures. (See **Fig.19.**) The method consists of the following steps: narrow titanium cladding steel plates are fillet-welded to form a frame on the circumference of the structure surface to be protected; then a thin gauge titanium plate is welded to the frame by indirect resistance welding to seal the protected surface. **Photo 5** shows the indirect resistance welder developed for this application. The welder is

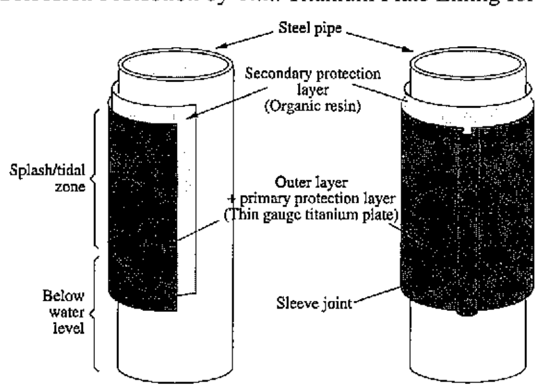


Fig.17 Titanium lining pipe piling **Fig.18 TP method**

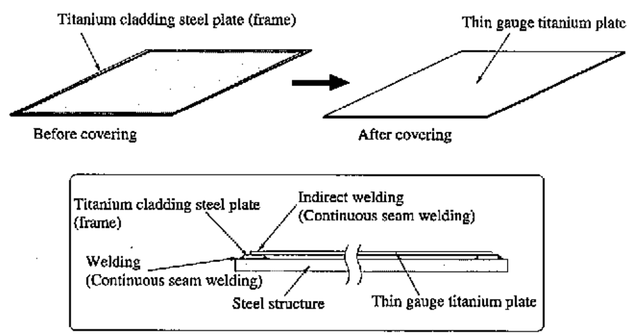


Fig.19 Corrosion protection method by thin titanium plate lining

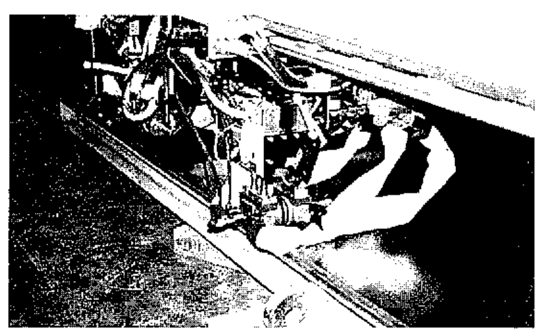


Photo 5 Indirect resistance welder

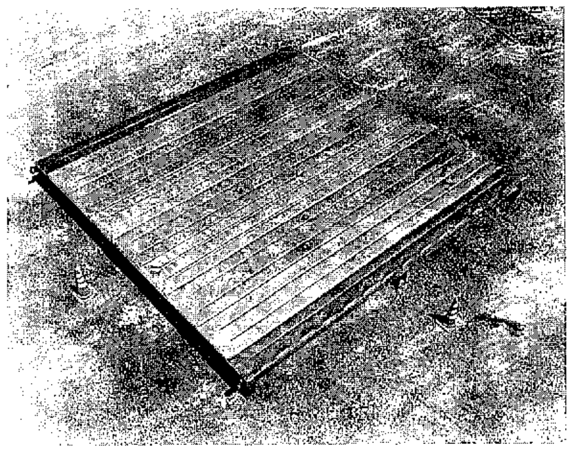


Photo 6 Application of thin titanium plate lining to real size test model

characterized by that the welding work is completed from one side of the welded material and that the protection work is applicable after the assembly of the structure as well, since the welder is capable of travelling.

Photo 6 shows a trial coating on a mock-up test structure. The method offers a low material cost by the use of thin gauge titanium plates and also a remarkably reduced cost by the use of a high efficiency welder.

6. Conclusion

Technology development activities were promoted for the purpose of making a very large floating structure (VLFS) practicable as a foundation structure that can be safely used for a very long period in the offshore environment. As the result of the activities, the following benefits have been attained and, thanks to these, technologies have been accumulated for designing and constructing a real-size scale VLFS:

(1) Due to its small stiffness because of the relatively small thickness, VLFS behaves predominantly elastically in waves. Facing this situation a wave response analysis method was developed which method could handle a floating body of any shape as an elastic body taking into account interactions between fluid and floating structure.

(2) Displacement reduction mechanisms were worked out for the purpose of controlling movements of VLFS in waves, seen pronouncedly near the ends, possibly jeopardizing stable operation of the service facilities to be constructed on it, and effectiveness of the mechanisms were confirmed.

(3) Methods were worked out for the analysis and design of the mooring system for VLFS and applied to the mooring equipment of the MEGA-FLOAT demonstration model of a 1,000-m class floating airport. Effectiveness of the developed methods is being verified.

(4) A series of methods for the construction of VLFS were developed including those for connecting floating units under offshore conditions. Different methods for different working conditions were proposed and verified so that the most suitable one may be selected in accordance with actual conditions.

(5) A corrosion protection method for ultra-long duration was developed, wherein titanium cladding steel plates are used in the splash/tidal zone of marine steel structures. Also was developed and verified a method for protecting uncovered surfaces at the joints left between the protected surfaces of the floating units when they are fastened together at the construction site.

Besides the above, a low-cost corrosion protection method was developed for an ultra-long duration of steel pipe pilings and floating marine structures by covering their surfaces with thin gauge titanium plates, and the method was brought to be applied to actual projects.

It has to be noted that some of the technologies introduced in this report were developed through the joint research activities with the Technological Research Association of MEGA-FLOAT (TRAMF).

Reference

1) Utsunomiya, T. et al.: Proc. 5th Int'l Offshore and Polar Eng. Conf., The Hague, 1995
2) Nakai, K. et al.: 13th Ocean Engineering Symp., Tokyo, 1995
3) Ohta, H. et al.: 14th Ocean Engineering Symp., Tokyo, 1998
4) Empirical Research on Use of MEGA-FLOAT for Floating Airport - Report of Research Activities in Fiscal 1998, TRAMF, Mar. 1999
5) Ultra-large Floating Marine Structure (MEGA-FLOAT) - Report of Research Activities in Fiscal 1997, TRAMF, Mar. 1999
6) Ultra-large Floating Marine Structure (MEGA-FLOAT) - Report of Research Activities in Fiscal 1995, TRAMF, Mar. 1999
7) Ultra-large Floating Marine Structure (MEGA-FLOAT) - Report of Research Activities in Fiscal 1996, TRAMF, Mar. 1997
8) Ohkubo, H. et al.: OMAE. 16th, Yokohama, 1997
9) Yago, K., Torii, T. et al.: Technoocean98, Kobe, 1998