CHAPTER 97

Studies on the Navigation Buoy for Strong Tidal Currents and Large Waves

by

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ABSTRACT

Up to the present time, some researches have been done about hydrodynamic forces and tensile forces on mooring cables and configuration of cables in uniform and ununiform currents.(1) Recently, the dynamic problems on the mooring system of buoy in waves are being studied by means of analytical and numerical methods. Authors have studied about a large navigation buoy exposed to strong tidal currents and large waves by means of model tests in an open channel and a wave tank.

INTRODUCTION

A big project of the construction of three long bridges linking between the Main Land of Japan and Shikoku Island is about to start almost simultaneously at the three routes. All of them will cross narrow straits with strong tidal currents which are dangerous paths in a point of view of safety navigation. One of them, the Akashi Straits of about 4 km width has a maximum tidal current velocity of 8 knots. And in addition, quite a many ships more than 2000 a day pass through the straits. About more than 90 % of them are small ships less than 1000 gross tonnage. These small ships have often caused many marine accidents in such narrow straits.

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During the construction work of the piers, it is expected that ship collisions against the boring towers, the erection piers and other temporary structures may happen during bad weather, thick fog or night. After the completion of the piers ships would also collide against the piers.

For the purpose of preventing the ship collisions against these structures, several kinds of equipments for security of ships navigating through the straits are required not only at the upstream and downstream sides of the piers but also on the piers to show and control the navigation channels of the ships.

As one of the equipments, navigation buoys equipped with electric lights, electric horns, radar reflectors and transponders were required to anchor at the upstream and downstream sides of the structures.

As was mentioned, the straits over which the bridges will span have strong tidal currents. And the maximum height of waves estimated at the Akashi Straits is as large as 7 meters.

A committe was organized by the Honshu Shikoku Bridge Authority in order to investigate and design the special buoys to withstand the severe environmental conditions.

DESIGN CRITERIA FOR THE BUOY

The committe has decided the design criteria for the buoy as follows.

(1) A maximum tidal current velocity of 8 knots

(2) A ten-minutes mean wind velocity of 45 m/sec

(3) A maximum instantaneous wind velocity of 60 m/sec

(4) A maximum wave height of 7 m

(5) A water depth of 100 m

(6) A maximum movable radius of 85 m

(7) Steel chains were recommended to be used for the mooring line, because synthetic fiber ropes, for example, nylon ropes are much inferior to chains in the shear strength and the durability though the weight per unit length is much less than that of steel chains.

PRELIMINARY MODEL TESTS

At the beginning of the investigation, three shapes of buoys which were circular cylindrical, ship- and discus-type buoys and two kinds of mooring systems which were single buoy system and two buoys system with a submerged mid-float were selected by the committe as the buoys to be studied.

The first step of the study is to evaluate the characteristics of three shapes and two mooring systems of the buoys in the tidal currents and waves. The outlines of the surface buoys and the submerged mid-float are shown in Figs. 1 (a),(b),(c) and Fig. 2.

The original three surface buoys were made nearly equally in the total weight which was about 4.2 tons to 4.5 tons, and in horizontal cross-sectional area which was 15.9 m^2 except the discus-type buoy which had a larger cross-sectional area of 50.3 m^2 because of a smaller draft.

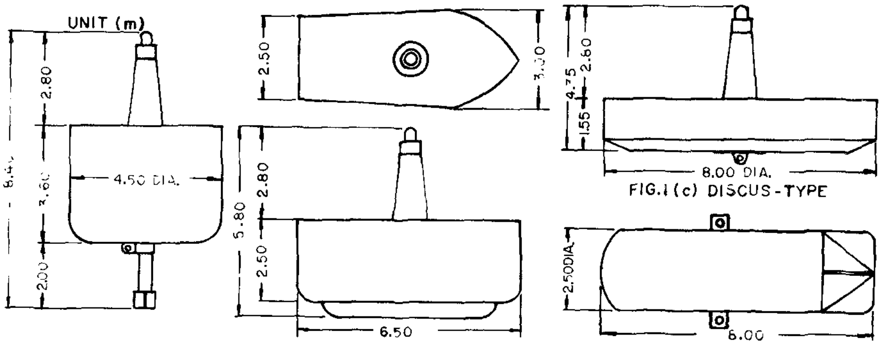


FIG.1 (a) CYLINDRICAL TYPE FIG.1 (b) SHIP-TYPE FIG. 2 MID-FLOAT

Fig. 1.Outlines of Surface Buoys Fig. 2.Outline of Mid-Float

According to the results of the preliminary model tests for the original three buoys, the circular cylindrical type buoy was not suitable for the special buoy because of large drag force exerted on the hull and consequently, larger tension acted on the mooring chains under the co-existence of tidal currents and waves.

REFORMED BUOYS

From the results of the preliminary model tests, ship- and discus-type were selected for the buoy hull and they were reformed in shape and diminished in dimensions on the basis of the fundamental plan of the mooring system as shown in Fig. 3. Fig. 3 (a) shows the case of two buoys system in deeper sea with a water depth of 100 m. Fig. 3 (b) shows the case of single buoy system in shallower sea with a water depth of 30 m. In such relatively shallow sea where the depth of water is shallower than about 100 m, single buoy system is better and more economical than two buoys system.

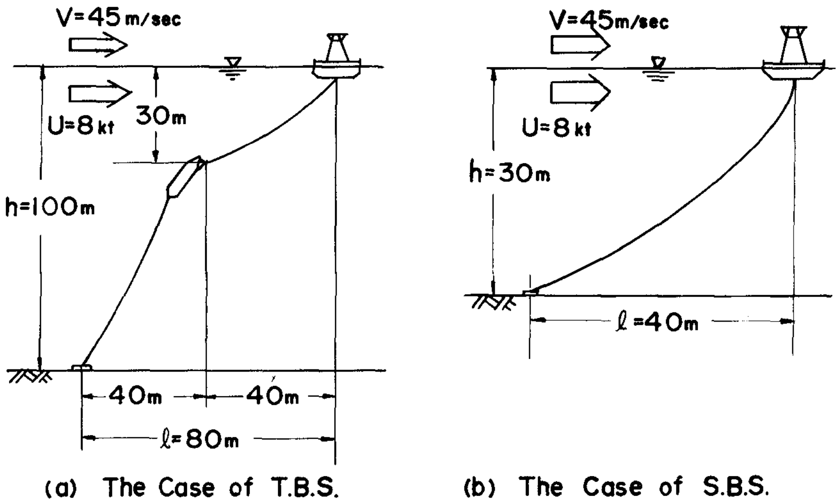


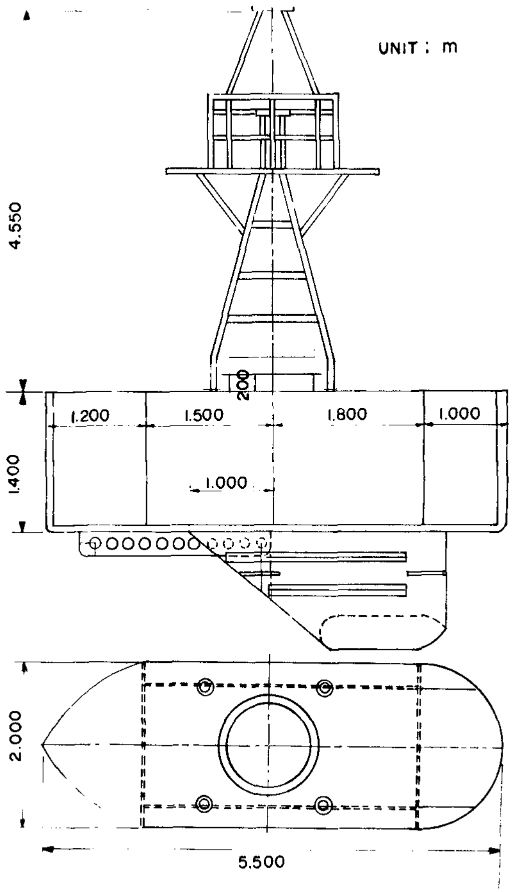
Fig. 3. Fundamental Plans of Mooring System

Fig. 4 (a) shows the outline of the reformed ship-type buoy. The total height from the top to the bottom of the reformed ship-type buoy is 5.99 m and the width is 2.0 m. The horizontal cross-sectional area is 9.5 m^2. The total weight is 5.5 tons. The total buoyancy is 13.7 tons. Fig. 4 (b) shows the outline of the reformed discus-type buoy. The total height is 5.55 m. The diameter is 4.5 m. The horizontal cross-sectional area is 15.9 m^2. The total weight and the total buoyancy are almost the same as ones of the ship-type buoy.

HYDRODYNAMIC FORCES EXERTED ON THE BUOYS

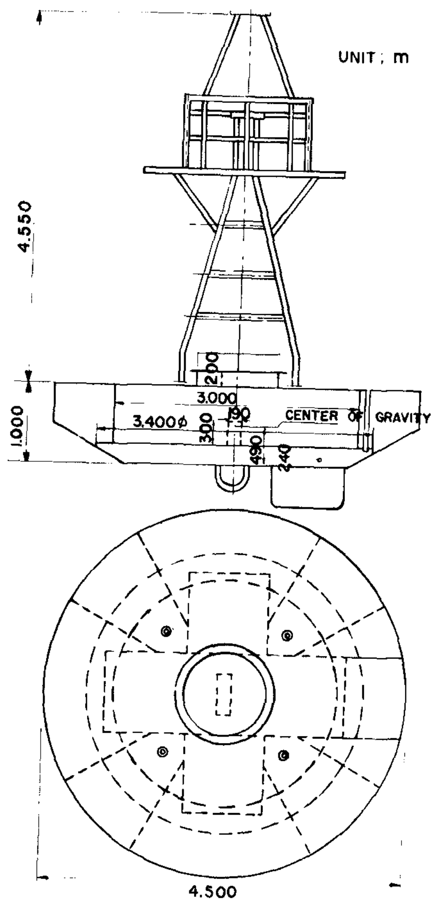
In the second step of the study, further model tests for the reformed buoys were carried out.

The hydrodynamic forces exerted on the reformed buoys by steady flows were measured. The scale of model to prototype was 1/20. For the experiments, an open channel, 40 m long, 1.2 m wide, 0.8 m deep with the maximum flow discharge of 550 l/sec, in Osaka City University was used. The total drag forces, including the wave making drag, the pressure drag and the skin friction drag, were measured by using a flat steel bar with 4 strain gages.



(a). Outline of reformed ship-type buoy

Fig. 4.Outline of Reformed Buoys



(b) Outline of reformed discus-type buoy

Fig. 4. Outline of Reformed Buoys

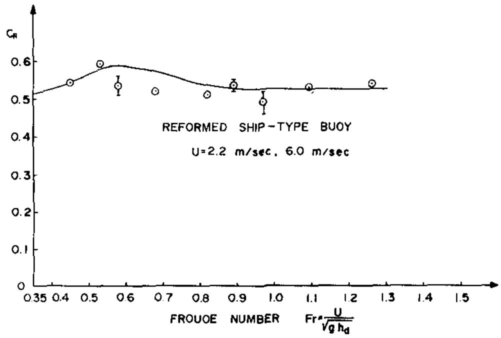
The hydrodynamic forces exerted on the buoys parallel to the current direction may generally be represented in the following expression.

$$F = \frac{1}{2} \rho C_R A U^2, \tag{1}$$

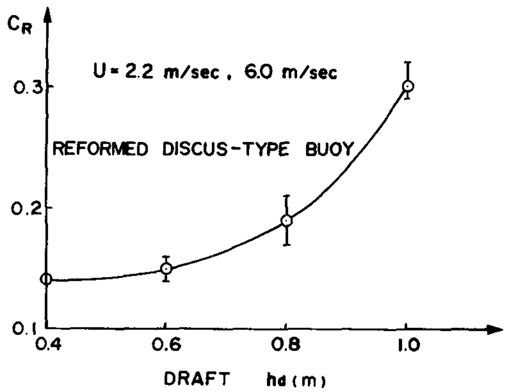
in which F defines the total drag force exerted on a buoy, A is the projected area perpendicular to the current direction, U denotes the current velocity, ρ is the mass density of water and C_R defines the total drag coefficient.

The total drag coefficients C_R of the reformed ship- and discus-type buoys are shown in Figs. 5 (a) and (b) .

Most of the total drag forces on the buoy may be the wave making drag for relatively large velocities. Consequently, C_R seems to depend on the shape, the draft of the buoy, h_d , and Froude Number $F_r = U/\sqrt{g\ h_d}$



(a) Reformed Ship-Type Buoy



(b) Reformed Discus-Type Buoy

Fig. 5.Total Drag Coefficients of Reformed Buoys

A negative up-lift force acts downwards on the surface buoys perpendicular to the current direction.[2] In order to investigate negative up-lift forces, the upper tensions on the mooring line were measured by using a small ring gage with two strain gages, and the vertical components of the upper tensions T_V were compared with the increases in the buoyancy of the buoy ΔP corresponding to the increases in the draft of the buoy in the current from the draft in the still water. The difference between T_V and ΔP is equivalent to the negative up-lift force. According to the experimental results, the negative up-lift forces on the reformed ship-type buoy seem to be 2 % to 4 % of the total buoyancy P_V which is equal to the weight of the water volume equivalent to the volume of the submerged part of the buoy. And the negative up-lift forces on the reformed discus-type buoy seem to be 3 % to 9 % of P_V.

According to the results of the experiments concerning the negative up-lift forces on the another model buoy of the circular cylindrical shape with a hemispherical bottom as shown in Fig. 6, the negative up-lift forces seem to be 1 % to 3 % of the total buoyancy. Fig. 7 shows the one example of the pressure distribution on the bottom surface at $\theta = 0°$, in which θ defines the horizontal angle measured from the up-stream stagnation point.

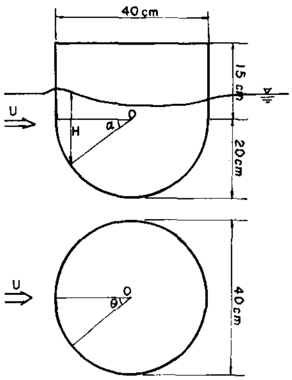


Fig. 6. Circular Cylindrical Type Buoy with Hemispherical Bottom

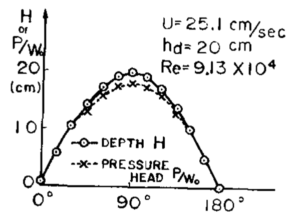


Fig. 7. Pressure Distribution on the Hemispherical Bottom

The solid line shows the depth H of the bottom surface from the water surface. The dotted line shows the pressure head distribution on the bottom surface. The difference between them contributes to the negative up-lift force.

For the buoys of such shapes as used in our experiments, it seems that the negative up-lift forces on the buoys do not have so important meaning from a practical point of view.

MODEL TESTS IN WAVES

1/15-scale model tests concerning the reformed buoys exposed to the tidal currents and waves were carried out in a large wave tank, 60 m long, 10 m wide and 2.5 m deep, in Osaka City University. For the purpose of simplification of model tests, it was assumed that the influences of the tidal currents and waves exerted on the moored buoy are independent. The effects of the hydrodynamic forces on the moored buoy by the tidal currents were simulated roughly by the use of a special coil spring with constant reaction, as shown in Fig. 8, in a wave tank. This special coil spring has such a characteristic that the reaction is almost constant regardless of the elongation. The reaction P is represented by following equation.

$$P = \frac{E\ I}{2\ R_0^2} \qquad (2)$$

in which, E is Young's modulus, I is geometrical moment of inertia of coil spring and R_0 is a radius of curvature of coil. (See Fig. 9) This spring is coiled around a pully with very small friction. The coil spring was set in a case as shown in Fig. 10.

At the beginning of the experiment, the horizontal force equivalent to the total drag force on the buoy, that is, the horizontal component of the upper tension on the mooring chains calculated by Wilson's tables and diagrams[(1)] was given on the bottom of the moored model buoy by pulling with the special coil spring. (See Fig. 11) The weight per unit length of the model chains was taken $(1/15)^2$ times as much as the prototype on the basis of Froude law of similarity. As shown in Fig. 12, the curve of the mooring chain in the wave tank does not agree with the curve of the chain in the uniform tidal current. The model chain forms the catenary curve in the wave tank. Moreover, the upper end of the mooring chain in the model tests moves to more downstream side than the location estimated in the uniform currents. These caused the upper tension T_u on the mooring chain in the model tests to become smaller than that in the uniform tidal current, because the effect of the hydrodynamic force exerted on the mooring chain by tidal currents was not simulated in the model tests. In order to simulate the effect more correctly, the horizontal force given by the coil spring and the weight per unit length of the mooring chain were taken larger than those calculated, but leaving the length of the mooring chain just as it was.

Fig. 8.Special Coil Spring with Constant Reaction

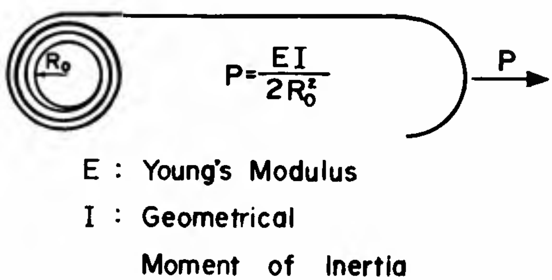


Fig. 9.Special Coil Spring with Constant Reaction

Fig. 10.Special Coil Spring Set in a Case

Fig. 11.Model Buoy Pulled with the Special Coil Spring

As the result of this adjustment, both the upper tension and the curve of the mooring chain in the model tests almost agreed with calculated ones in the tidal currents.

By the way as above mentioned, the initial equilibrium condition of the moored buoy in the tidal currents was formed in the wave tank as shown in Fig. 13. The upper tension on the mooring chain was measured by the use of a small ring gage with two strain gages. Fig. 14 shows the relationships between the upper tensions and wave heights at a wave period of 8 sec for the single buoy system of the reformed ship- and discus-type buoys. The criteria of the mooring buoy used in Fig. 14 were a water depth : 30 m, a maximum movable radius of a buoy : 40 m, a tidal current velocity : 8 knots, a ratio of chain length to water depth : about 1.70 and a weight per unit length of the mooring chain in water : 33.5 kg/m.

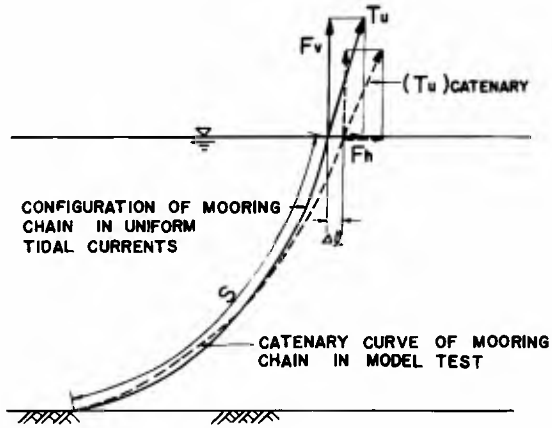


Fig. 12.Curves of Mooring Chains

Fig. 13.Initial Equilibrium Condition of Moored Buoy

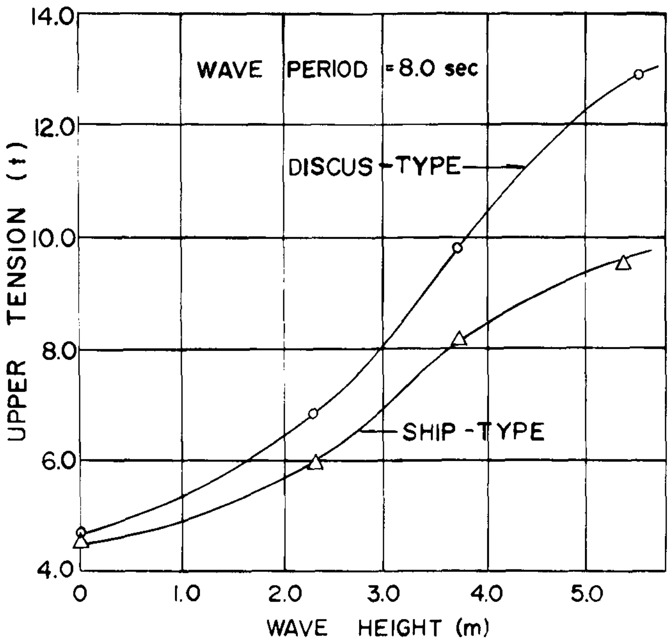


Fig. 14. Relationships between the Upper Tensions and Wave Heights

From Fig. 14, it may be concluded that the upper tensions for the discus-type buoy are larger than those for the ship-type buoy though their initial upper tensions are almost the same. The reason may be attributed the fact that since the discus-type buoy has larger bottom area than the ship-type buoy, the impact forces caused by the upward motion of the wave on the bottom of the discus-type buoy are larger than those on the ship-type buoy.

Further detailed experimental results for the reformed discus-type buoy under the same mooring criteria for wave periods of 6.0 sec, 8.0 sec and 10.0 sec are shown in Fig. 15. Fig. 15 shows that shorter period-waves may cause larger upper tensions on the mooring chains than longer period-waves.

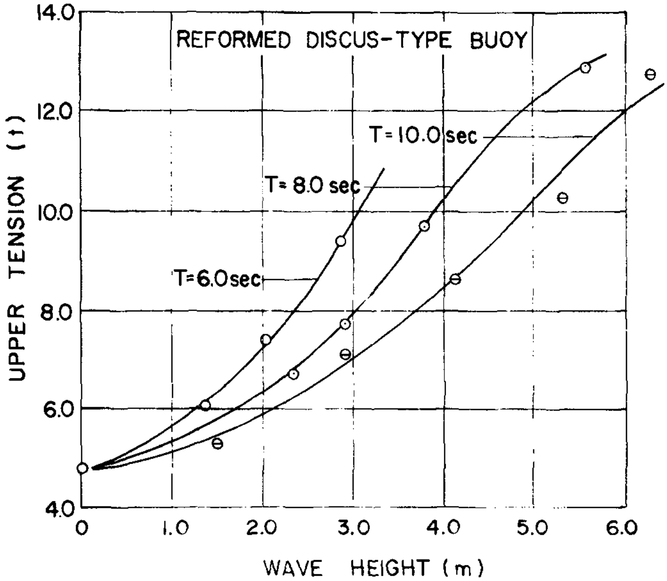


Fig. 15.Relationships between the Upper Tensions, Wave Heights and Wave Periods

OSCILIATORY MOTIONS OF BUOYS

The reformed ship-type buoy has two periods of the free oscillation of 4.4 sec for tolling and 2.4 sec for pitching, moreover their damping is very slow. On the other hand, the discus-type buoy has one period of the free oscillation of 2.1 sec regardless of the mode of oscillation except heaving, besides the damping is very fast. Therefore the ship-type buoy is apt to roll and pitch with large inclination caused by the resonance with waves with period of 2 sec to 4 sec, while the discus-type buoy does not oscillate so much as the ship-type buoy does because of its large damping effect, even in waves with a resonant period.
Waves with periods of 2 sec to 4 sec have been often caused by winds with velocities of 10 m/sec to 15 m/sec in the Seto Inland Sea. In addition,

waves generated by ships which navigate through the straits also have such a shorter periods.

CONCLUSION ON SHAPE OF BUOY

From a practical point of view, it may be concluded that the ship-type buoy is not suitable for the special buoy. Finally, the discus-type buoy was selected for the special buoy, though the upper tension is larger than that in the ship-type buoy.

TWO BUOYS SYSTEM WITH SUBMERGED MID-FLOAT

According to the results of additional experiments for the two buoys system, it was found that the upper mooring chains tend to twist about the mid-float at slack tide. But if the length of the upper mooring chain is taken shorter, the large impact forces are caused on the mooring chains by the movement of the surface buoy due to the waves.

PROTOTYPE BUOY

On the basis of the results of these studies, the discus-type buoy was designed and several were manufactured in 1971 for the practical use.

Two discus-type buoys in the Akashi Straits and other discus-type buoys in the Bisan Straits have been moored for the navigation buoys in single buoy system to show and control the navigation channels to ships navigating around the boring towers erected in those straits. (Fig. 16 and Fig. 17)

ACKNOWLEDGEMENT

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(2) S.Nagai : Hydrodynamic Forces on Light Buoy in Strong Tidal Currents, 11th Conf. of I.A.H.R., Sept., 1965.

Fig. 16

Fig. 17

Fig. 16 and Fig. 17. Discus-Type Buoy Moored in the Akashi Straits