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港湾空港技術研究所
資料

TECHNICAL NOTE
OF
THE PORT AND AIRPORT RESEARCH INSTITUTE

No. 1151　March 2007

弾性を有する浮体の運動と係留張力に関する多方向波実験

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弾性を有する浮体の運動と係留張力に関する多方向波実験

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要　旨

建設工期が短い海上施設として大型の長大ポンツーンの設置が注目されており，メガフロートと呼ばれる小型海上空港の実証実験も実施されてきた．また，海上空港の拡張案の一試案として大型浮体式空港が検討される場合もあり，河口部における流れを阻害しない浮体形式として平板による半没水型（セミサブ型）浮体の部分的な採用が検討された．そこで，本実験では，①単純な矩形浮体（ポンツーン）とセミサブ型および両者を組み合わせた複合浮体構造の動揺量と係留力を検討した．また，②単純な矩形浮体の動揺低減のための消波工を検討した．

実験の結果，多方向不規則波中でも，ポンツーン型に比べて，セミサブ型浮体の動揺量が小さくなることが確認できた．ポンツーン型大型浮体は構造が単純で，メンテナンスコストなどを除くと設置条件によっては工費が比較的少ないという長所を有するが，作用波高が吃水と同規模になると浮体端が水中より浮き上がり，スラミング現象によって上下動が大きくなってくる．複合浮体構造を用いた場合には，セミサブ部分であっても鉛直変位の振幅は，ポンツーン型とほぼ同程度になり，セミサブ型の長所を活用することが困難であった．また，短周期波作用時に直立壁面で反射波が顕著に生じて，周辺海域へ影響を及ぼす短所を有する．

消波工としては，開口率 20%のスリット型動揺低減工を開発し，その効果を模型実験で検討した．長さ 750m の長大浮体の 1/50 縮尺模型を多方向不規則波も造波できる平面水槽に設置して，浮体動揺量と係留力を測定したところ，従来から提案されてきた水平板式と同程度の動揺低減効果を有することが判明した．またスリット式動揺低減工を取り付けた浮体の係留力は水平板式より小さくなり，浮体からの波の反射率は，0.5 程度まで小さくすることができた．

キーワード：長大弾性浮体，鉛直動揺量，係留力，多方向不規則波模型実験，動揺低減法

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Directional Random Wave Experiments on Motion and Tension of Elastic Floater

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Synopsis

A large floater with an elastic pontoon and with a semi-sub part is proposed for offshore floating facilities like an airport. The characteristics of floater motion in directional random waves were physically examined. The vertical displacement amplitude in the uni-directional waves became larger than in the multi-directional waves. The experimental results demonstrated the importance of the reproduction of wave directionality in the wave basin. The vertical displacement amplitude in the floater became the maximum at the sensor position attached on the downstream side for oblique incident waves. The displacement amplitude became smaller in the semi-submerged type floater than in the simple pontoon type. The vertical displacement of combined type floater was dominated in the similar motion to the pontoon part.

A slit member similar to the vertical wave-absorbing-type caisson was designed as a countermeasure against the large vertical motion of the pontoon. A line of triangle slit members were attached in every side face of the pontoon. The variation of displacement amplitude and the wave reflection coefficient were measured in the model test. The experimental results demonstrated that the wave-energy-dissipating-type slit members were effective as a countermeasure installment for the large motion, because the vertical displacement of the pontoon decreased without remarkable increase of mooring tension.

Key Words: Elastic large floater, Directional wave basin test, Vertical displacement, Slowly-varying wave drift force, Slit members of wave-energy-dissipating-type

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1. Introduction

Large floating structures (Mega-float) are widely considered in construction of offshore airports, offshore disaster prevention bases, maritime hotels and so on. Especially the application of an elastic large floater is considered in the extension project of several offshore airports (ex., Kado et al., (2005)). The elastic long plate is employed as the main body design of the floater because the elasticity of the board may reduce the share stress on the board exerted by sea waves. The floater is normally moored in the dolphin formed with jacket type or pier type offshore structures. In order to make the design of arrangement and dimension of the mooring system, we have to estimate accurately both the amplitude of floater and the wave-induced drift force.

The combination type floater combined with the simple pontoon and comb-shape semi-sub type floater is proposed and investigated as the offshore extension of the airport (Inoue et al., 2005). The comb-shape type is suitable to the offshore structure construction in the river mouth because the projection area on the water surface becomes small enough to keep smooth flush of river water. Meanwhile the pontoon type has the advantage of lower cost and easier production. Okawa et al. (2005a) conducted the physical model test on the vertical displacement of combine type floater in the scale model of 1/200. They derived that the motion of pontoon part increases when the wave period increases. The motion in irregular waves was not examined. Moreover the scale of experiment is too small to obtain the detail analysis data for floaters.

Kato et al. (2005) carried out the motion test of the comb-shape semi-sub type floater with the length of 1080m in the prototype in the uni-irregular wave basin. The scale of the model test is 1/100. They derived that the dimensionless vertical motion amplitude of the floater is not influence by the wave height when the wave height is smaller than 4m. They conducted a numerical simulation to estimate the motion of an elastic semi-sub floater but the derived displacements do not agree with the measured ones. Therefore a more accurate simulation model should be developed.

Okawa et al. (2005b) investigated the drag and added mass coefficient of comb-shape component the semi-sub floater using the model of 1/50 scale. They employed three components to measure wave-exiting forces acting on the comb-shape component. The purpose of the experiment is not measuring the motion of elastic floaters. In order to develop a new numerical model to estimate the motion of the large elastic floater combined of pontoon and semi-sub types, the experimental data for verification is necessary. The vertical displacement and slowly-varying drift force in the combination floater model with large scale becomes a key term to consideration of the numerical model validity.

The slowly-varying drift force acting on the floater becomes dominant in the irregular wave condition representing the actual sea wave propagation. Several physical and numerical studies have been carried out to estimate the oscillating drift force in irregular waves. (ex. Hsu et al., 1970) Few studies were done on the investigation of the characteristics of oscillating drift force in directional random waves. In the deep sea condition, sea waves are represented as the directional random waves in which each component wave has different amplitude, frequency and direction.

In the paper, we carried out a physical model test on the motion of a floater and the slowly-varying drift force on a large floating structure with directional random waves in order to prepare the verification data for future numerical model for offshore floating airports. The following three types of floaters are examined to compare the applicability of each floater; a) a simple pontoon type with small draft, b) a semi-sub floater with comb-shaped foots with large draft and c) the combination type of the both. The draft depth of pontoon part in the combination type is the same to that of a) type and the semi-sub part to that of b) type. The model scale is 1/50 that is allowable in the basin.

The motion of a simple pontoon type floater became remarkably large compared with that of a semi-sub type floater. The motion of combination type floater was dominated by the motion of pontoon type. In the later part of the paper, therefore, we also examined and proposed a new motion reducer that was attached on the side faces of the floaters. The motion, the mooring tension and the wave reflection coefficient were examined on a pontoon type elastic floater with the motion reducer.

2. Experimental Condition

2.1 Arrangement of wave basin and model

Figure 1 shows the arrangement of a wave generator and the model floater. The basin has a multi-face directional random wave generator with two faces of wave maker paddles (Hiraishi et. al. 1998). Each paddle is 60cm wide and 100cm high. The paddles are operated in the piston type mode and connected in vertical hinges with neighboring paddles. In the figure, the segmented snake type directional wave makers are arranged along the upper and left sides. The principal wave direction of directional waves in the experiment was 60 and 90 degrees counter-clockwise inclined from the long-side centerline of the floater.

The significant wave height $H_{1/3}$ and period $T_{1/3}$ was 2.1m and 8s or 4.2m and 8s in prototype respectively. The multi- and uni-directional waves with the JONSWAP (Goda, 1987) type frequency spectrum were reproduced and the heaving amplitude in several specified points and the mooring tension were observed in the model test. The Mitsuyasu directional function (Goda et al.,1975) was employed as the wave energy distribution function determining the characteristics of directional waves. Regular wave trains with 2m in height are also generated for the period range from 6s to 14s in prototype. The regular wave trains are employed for the fundamental bending studies.

The model floater represents an offshore airport that was considered in construction in the Japanese coast. The length and width of the floater is 750m and 150m respectively in prototype. The model was set in the directional wave basin with the L-shape arrangement of the wave generating paddle. The model floater is scaled of 1/50. The prototype floater is to be constructed as a floater with elasticity for the reduction of bending moment by the wave action. In the prototype, the elasticity of structure is evaluated by a numerical computation with a large number of segments. The evaluated prototype elasticity is 6.61×10^{8}kNm per unit meter of the pontoon type and 1.50×10^{8}kNm for the semi-sub type as shown in **Table 1.**

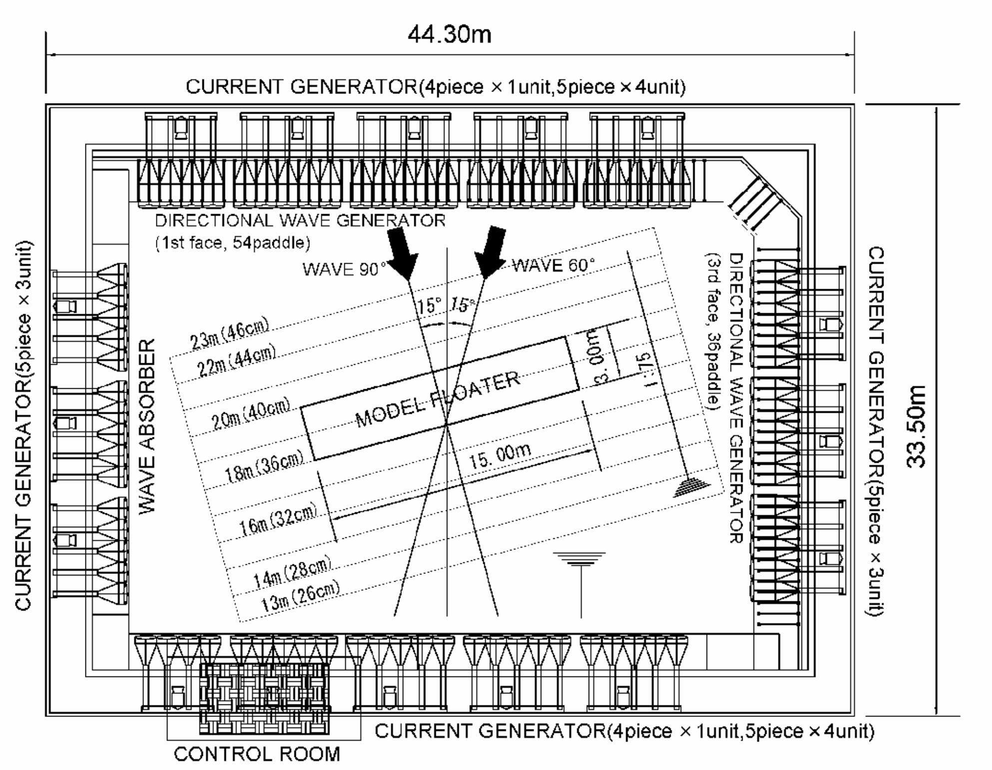


Figure 1 Arrangement of model floater in directional random wave basin

Table 1 Comparison in elasticity of prototype and model floater

Elasticity per unit m	Prototype	Model (target)	Model (product)
Pontoon-type	6.61x10^8 (kNm)	1.06x10^2 (kNm)	1.09x10^2 (kNm)
Semi-sub type	1.50x10^8 (kNm)	2.40x10^1 (kNm)	2.41x10^1 (kNm)

(1) Whole view of model floater

(2) Detail of foot piers of semi-sub type

Photograph 1 Overview of model floater

The model floater should represent suitable elasticity to the scale law derived from the prototype design condition. The three type of floater was adopted in the comparison test. The first is the simple pontoon with the draft of 1.5m, and the second the semi-sub type floater. The third one is the floater combined of pontoon and semi-sub parts. The target elasticity of scale model is derived in a simple calculation for the assumption of Froude's scale law. The target model elasticity is described in Table 1 for the case of pontoon and semi-sub type.

The hydraulic model of floater should have target scaled elasticity in Table 1. We employed an aluminum board and polyurethane plate to reproduce the target elasticity as the material and arrangement employed in the model floater is different from those utilized in the prototype float. The model elastic board was made from the aluminum plate attached with the polyurethane sheet under the plate.

One unit of model floater is 3m long and 0.94m wide because of the size limitation of aluminum plate that we can purchase in market. For the semi-sub type floater, the upper plate is made from the combined board of thin aluminum and polyurethane and the lower part (foot part) is made from only the rigid mattress (urethane foam). The elasticity of model floater determined in the thickness of aluminum and polyurethane board is slightly different from the target. We chose the materials and checked the reproducibility of elasticity in measuring the displacement of the floater under the assigned vertical load.

The draft of the floater is 1.5m in the prototype pontoon type and 11m in the semi-sub type respectively. The water depth at the center of floater is 19m in prototype. **Photograph 1** shows the over view of the semi-sub floater model.

For the future development of the numerical model, we carried out the bending test on water. The vertical displacement of the model floaters on water was measured in the staff observation when the mass weight was put on the center of each floater. The weight at the center was 1N for the semi-sub and 3N for the pontoon type model floater.

Figure 2 shows the measured vertical displacement of model floater with the center load. The rigid line in the figure corresponds to the displacement of pontoon-type and the light line with rectangular symbols to the displacement of the semi-submerged type floater respectively. The profiles of displacement curves become the up-side-down bell shape. In the figure, the displacement profile is not perfect symmetry because the model floater is made from asymmetrically joined panels.

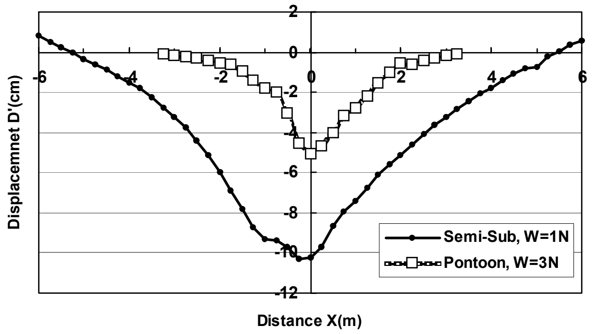


Figure 2 Displacement in loading test

The joints between two panels are done in screw bolts. The strength of bolts may have slight variations from place to place.

2.2 Sensor for measurement

At first we carried out the measurement of motion of three types of floaters. The vertical displacement of each sensor was monitored in the raiser displacement tracers.

Figure 3 shows the location of measurement sensors in the vicinity of model floater. The reflection sheets of tracer were put on the diamond shape symbols in Figure 3.

In Fig.3 the triangle location of (Ch.59, 60, 61) represents the tension sensor in the mooring line composed of the linear spring. The diamond shaped indications on floater correspond to the laser displacement sensors for heaving motion. The wave height was measured in the sensor expressed by circle. The drift force acting on the floater is obtained in the time-dependant tension on the mooring line. The combined type has the semi-sub part in the left half side and the pontoon in the right in Fig.3. The semi-sub type is usually more stable and more expensive than the pontoon type. In the combined type, the semi-sub type floater is employed in the specified area like the mouth of river where the pontoon may disturb the river flush.

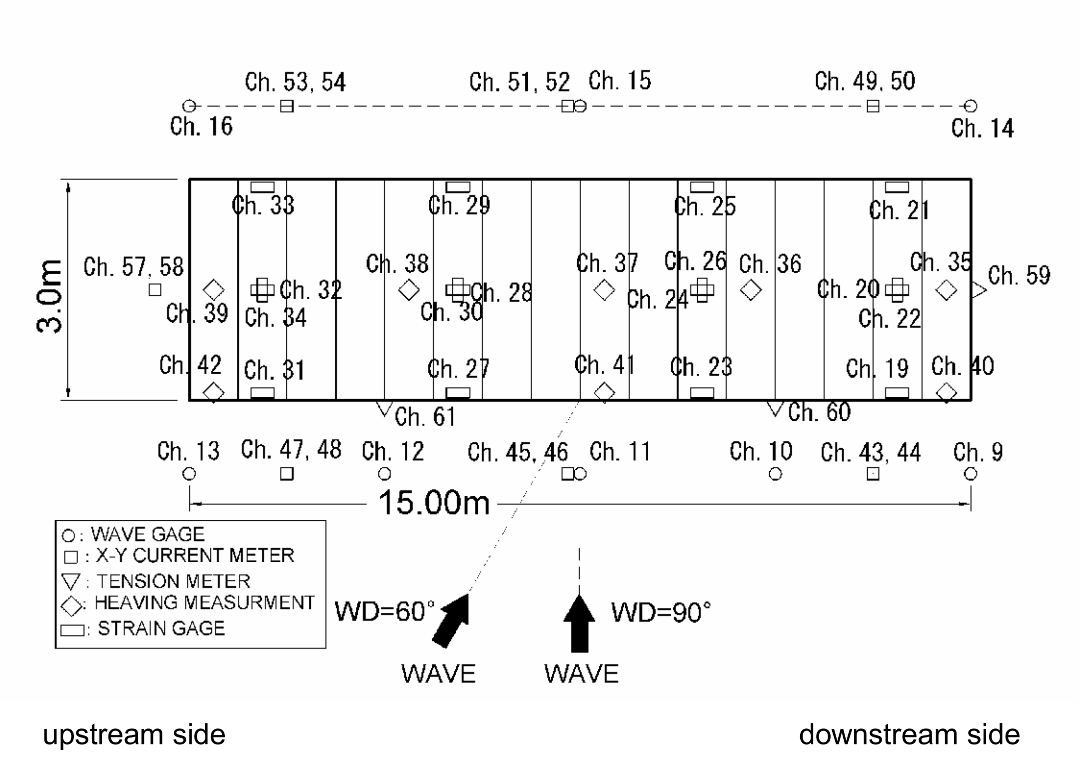


Figure 3 Location of measurement sensor on float
(Ch.35 and Ch.37 is indicated as Point 35 and Point 37 respectively in the following sessions)

3. Motion of Floater

3.1 Comparison in uni- and multi-directional waves

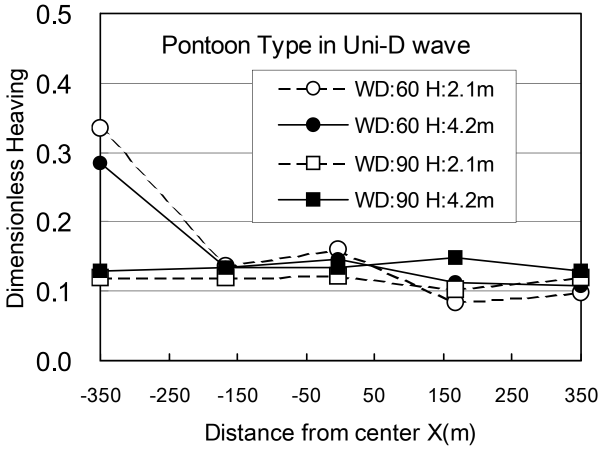
By analyzing the time dependent vertical displacements at each observation points, we obtained the significant amplitude of heaving motion. **Figure 4** shows the dimensionless significant vertical motion amplitude of observed points in the uni- and multi-directional wave conditions. Fig.4(1) corresponds to the case of uni-directional waves. The horizontal axis corresponds to the location of measurement points. The figure shows the amplitude of pontoon type floater with the normal (WD:90 (beam sea)) and oblique (WD:60) incident waves in the vertical axis. In the figure the amplitudes for the both cases of $H_{1/3}$=2.1 and 4.2m are analyzed.

The dimensionless amplitudes derived as the ratio of heaving amplitude to incident wave height in case of smaller wave height are almost equal to those in the larger wave height. The dimensionless heaving amplitude may receive little influence from the wave amplitude when the wave height is smaller than 4.2m. In the study, the heaving at observation points corresponds to the vertical displacement measured in the laser sensors. The rolling components of floater are included in the measurement location near to the floater side. The rolling components is not eliminated because the measured displacement should be employed directly in the designing the floater forms.

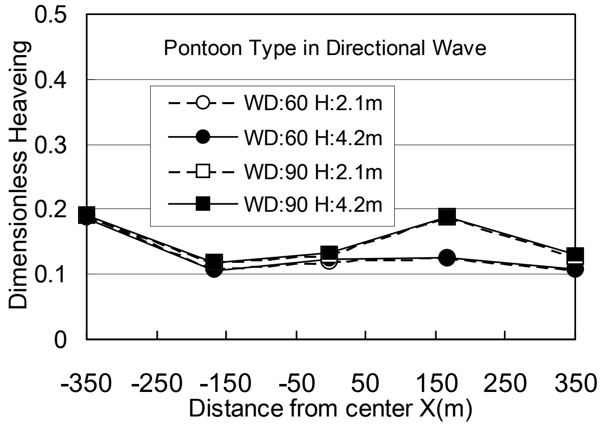
The rectangular indication in Fig.4(1) shows the spatial variation for normal incident waves while the circle oblique incident waves. In the region near to the central line, the heaving amplitudes are not remarkable in the both incidents. For oblique incident wave case, the heaving amplitudes become remarkable in the downstream side for wave direction. The amplitudes in the downstream side become about three times larger than those in the upstream.

Fig.4(2) shows the variation of heaving amplitudes in the pontoon type floater for the case of multi-directional wave cases. The meanings of indications are similar to the case of uni-directional waves. The dimensionless heaving amplitude in the normal incident becomes slightly peaked at x=150m. The amplitude is larger than that in the uni-directional wave case. In the downstream the dimensionless amplitude increases compared with the amplitude in the central line. However the increased amplitude at the floater edge of downstream side in the multi- directional waves becomes smaller than that in the uni-directional wave.

Therefore the wave directionality may be more important in the oblique incident wave condition and the heaving amplitude in the downstream side becomes more severe in case of uni-directional waves.



(1) for case of uni-directional waves

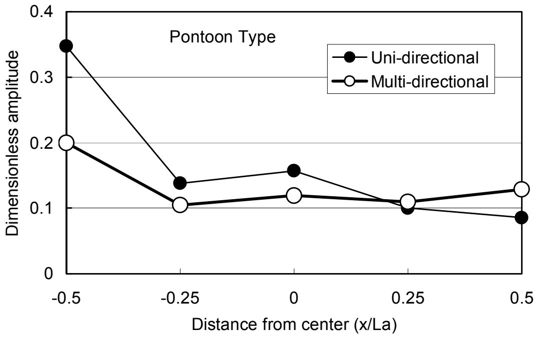


(2) for case of multi-directional waves

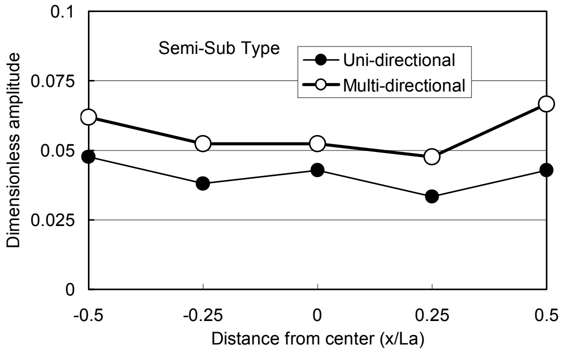
Figure 4 Variation of dimensionless vertical motion amplitude of pontoon type floater

Figure 5 shows the comparison of vertical motion along the center line of each floater. The indication of L_a represents the total length of floater. The negative axis corresponds to the pontoon type in case of the combination type floater. The wave height and angle is 2.1m and 60 degree respectively. In the pontoon type floater (Fig.5(1)), the difference at the most downstream side (x/La=-0.5) becomes remarkable as mentioned in former part of this session.

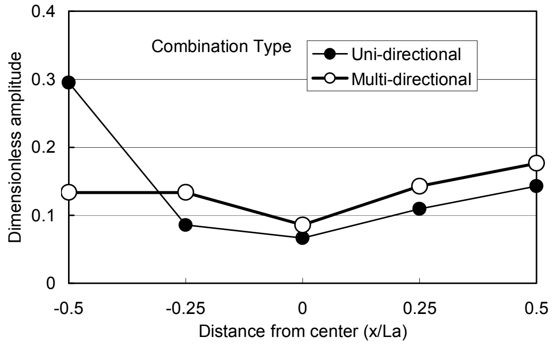
In case of the semi-sub type floater (Fig.5(2)), the amplitude becomes larger in the multi-directional waves in the whole region of floater. Meanwhile the downstream side motion becomes much larger in the combination type floater as shown in Fig.5(3). The motion amplitude of semi-sub part of combination type becomes larger in the multi-directional waves. Therefore the amplitude of vertical motion in the floater becomes critical in the uni-directional wave condition if the floater is composed of the pontoon type. The motion of semi-sub part becomes larger in the multi-directional waves.



(1) for case of pontoon type



(2) for case of semi-sub type



(3) for case of combination type

Figure 5 Variation of vertical displacement of each floater

The motion amplitude varies according with the wave directionality. The experimental results in the multi-directional wave case become inevitable because the prototype wave condition is similar to that of directional waves.

3.2 Comparison in floater-type

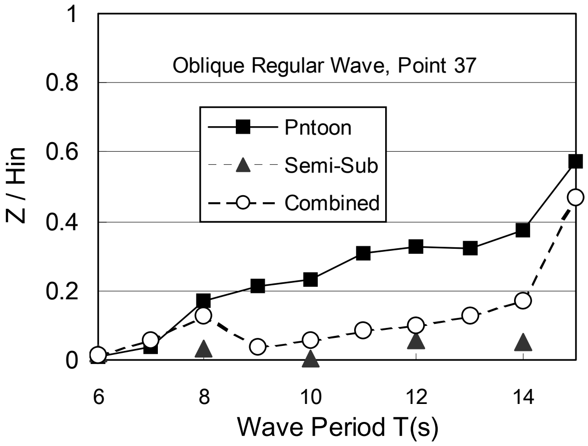
Figure 6 shows the heaving amplitudes of each floater type in regular waves. The point 35 corresponds to the edge in downstream side and the point 37 central measurement point. The figure shows the dimensionless heaving amplitude in the oblique incident regular wave (H=2m, WD:60). In the comparison for floater type, the amplitudes of pontoon type become larger than the other types in whole period region. The amplitudes of semi-sub type floater are small and they are stable as the wave period varies. The combined type floater has a pontoon part in downstream side.

The amplitudes of combined type floater are still smaller than those of pontoon type, but the differences between the amplitudes in the both types are not significant. The combined type floater shows the spatial distribution of heaving amplitude similar to that in pontoon type. The difference between the pontoon and combined types decreases as the wave period decreases. The amplitude in downstream side (at Point 37) becomes especially remarkable due to wave action to the side walls of pontoon.

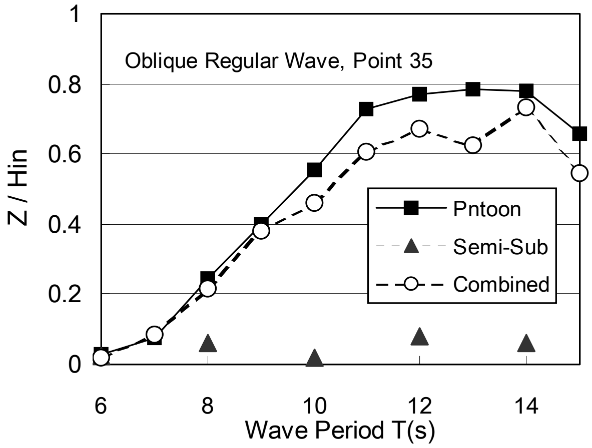
The motion in pontoon side may give the influence to the motion in semi-sub part significant. The heaving amplitudes of the pontoon and combined floater types become remarkable in long period waves with the period of 10 to 14s. The long waves (swells) are more critical to determine the size and number of mooring facilities. The design condition inside a bay is T=8s. in the design condition, the dimensionless heaving amplitude became about 0.2.

The experimental results for different type floaters demonstrate that the semi-sub type floater is suitable to reduce the vertical displacement of floater. Generally speaking, the construction cost of semi-sub floater is much higher than the simple pontoon type. To decrease the cost, the combination type should be applied in the coastal area. The improvement to reduce the vertical displacement of combined type floater should be carried out immediately.

The horizontal fin plates may become countermeasures for large vertical displacements.



(1) at Point 37 (Center)



(2) at Point 35 (Downstream)

Figure 6 Comparison of heaving amplitude in oblique regular waves

4. Variation of mooring Tension due to Drift Force

4.1 Analysis method

We analyzed the low frequency tension due to the wave drift force in the moving average method in which the short period components could be removed. The mooring forces are obtained at the points of 59, 60 and 61. We assume the mooring force varies according to the oscillating drift forces and the statistical analysis of mooring force is essential to the understanding of oscillating drift forces. The drift force due to regular wave train acting a pontoon is expressed as follows;

$$F_{RD} = \frac{1}{2} C_{sd} \rho g \left(\frac{H_{1/3}}{2} \right)^2 L_a \qquad (1)$$

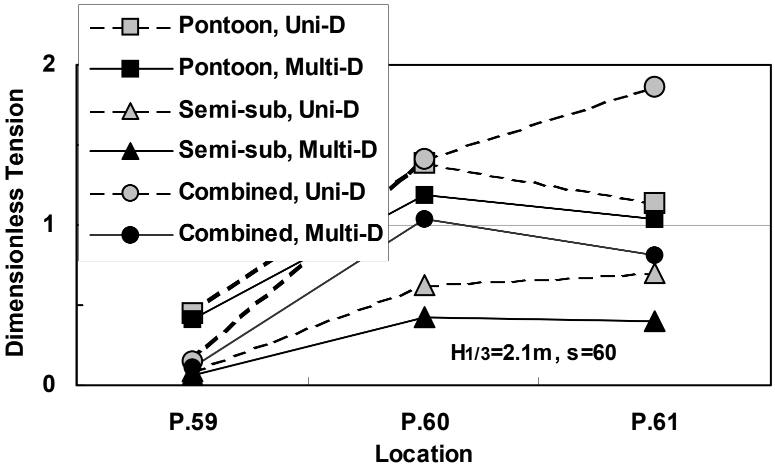
The indication ρ, $H_{1/3}$ and La represents the water density, incident wave height and length of floater respectively. The coefficient of C_{sd} represents the drift force coefficient determined from the wave reflection rate in floater and the maximum is 1.0. We calculated the dimensionless drift force as the ratio of measured force to F_{RD} with C_{sd}=1.

4.2 Variation of slowly-varying drift force

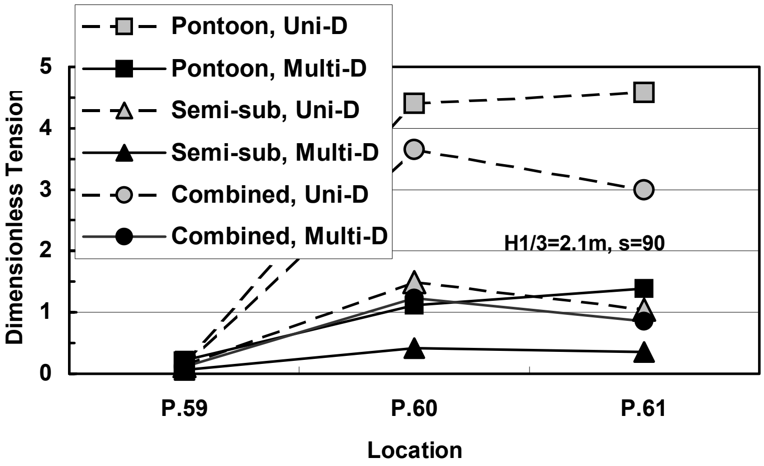
We mainly compared the significant amplitudes of oscillating tensions induced in the uni- and multi-directional waves. **Figure 7** shows the variation of dimensionless significant amplitude of slow drift tensions. The acting wave direction is 60 degree in Fig.7(1) and 90 degree in Fig.7(2). The significant tension in point Ch.59 was much smaller than the tension acting in Ch.60 and 61 because the point Ch.59 is located in the short side of floater. In Fig.7(1), the amplitude of tension in Ch.60 and 61 became the maximum in case of pontoon.

The acting tension in the combined type floater became similar to those in the pontoon type. The pontoon part in floater may cause the significant influence to the total drift force even if the pontoon part becomes a half of total length. The combined type floater may be useful to reduce the total construction cost but the motion and mooring tension becomes larger than the semi-sub type floater. Therefore the merit of using the combined type floater is not so large. The semi-sub type floater is more benefit when the reduction of drift force is important. The slow drift tension becomes smaller in the multi-directional waves than in the uni-directional waves in the all cases.

The difference between the significant dimensionless tension due to multi- and uni-directional waves become remarkable in the case for wave direction of 90 degree shown in Fig.7(2). For example, the dimensionless tension acting on Ch.61 of the pontoon type floater becomes third times larger in the uni-directional waves than in the multi-directional waves. Therefore the evaluation of wave directionality in the target sea area is important to determine the scale and dimension of mooring systems.



(1) for case of wave angle, 60 degree



(2) for case of wave angle, 90 degree

Figure 7 Variation of dimensionless tension due to oscillating drift force

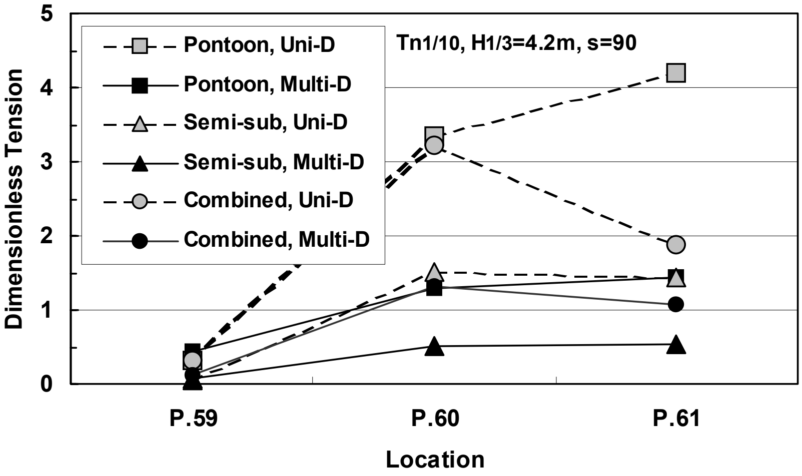


Figure 8 Variation of dimensionless tension for case of $H_{1/3}$=4.2m

Figure 8 shows the variation of significant amplitudes of oscillating wave forces in large wave with height of 4.2m. The dimensionless amplitudes of oscillating forces are almost equal to the case in the smaller wave case. The influence due nonlinear wave phenomena like breaking is not significant because the dimensionless force does not change when the wave height increases.

5. Countermeasure to Vertical Motion

5.1 Frame of countermeasures

We discussed the hydraulic experiment of large elastic floating structures and examined their vertical displacements in the former sections. As the results on experiments, we concluded the amplitude of vertical displacement at the pontoon and combined type floater edges increased as the incident wave height increased. The construction cost of pontoon type floater becomes relatively small compared with the cost of semi-submerged type floater because the pontoon type floater is composed with several simple rectangular boxes. However the amplitude of vertical motion might become relatively large when the incident wave height becomes almost equal to the draft of floater. The wave reflected from the vertical side may cause severe influence to marine environments and navigation of fishery boats. One of reasons that cause the large displacement is slumming phenomena induced by the up-lift force due to wave. The countermeasures to reduce the floater displacement and reflection are inevitable when we employ the elastic floater in real sea situation.

In the two dimensional experiments, Ohta et al.(2002) proposed a horizontal plate attached with the pontoon side to reduce the vertical motion and reflected wave heights. The vertical curtain wall, L-shape fin and so on are also studied as the countermeasures to reduce the vertical motion (Masanobu, 2003). The proposed systems, however, was not tested in a three dimensional wave basin. The wave reflection coefficient in the modified floater has been tested in a two-dimensional wave tank but it is not investigated in three-dimensional wave conditions. Another subject is variation of mooring tension due to drift force. Shimada (2002) demonstrated that the slowly drift force may increase when the horizontal plate is attached.

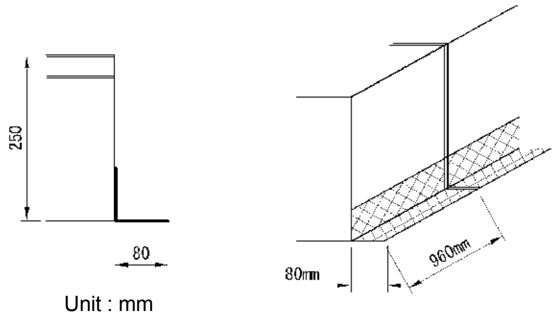
In this session we propose a new countermeasure system to reduce the vertical motion and wave reflection. The system is composed the triangle slit members similar to those in the vertical wave dissipating caisson. The slit members with triangle shape are attached on side face of pontoon floater. The wave energy may be reduced in the space surrounded in the slit members and the reflected wave height and vertical displacement decreased. Masanobu et al. (2005) studied on the effect of vertical slit type wave absorbers and concluded that the wave reflection coefficient became 0.5 in a two dimensional model test. Their system is similar to our countermeasure model. But we have developed individually without any information exchange before the paper publication.

5.2 Variation of floater displacement

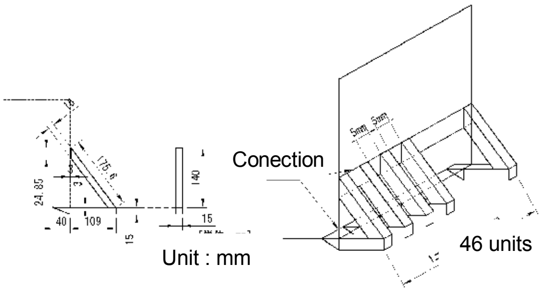
The test floater is the same to the piece employed in the former sessions. The length, width and draft of pontoon become 750m, 150m and 1.8m respectively in the prototype. The regular waves with H=2～4m, T=6～16s and irregular wave with $H_{1/3}$-4.2m and $T_{1/3}$=8.2s are employed. The wave energy concentration parameter S_{max}=10 and the JONSWAP type wave spectrum were employed. The wave direction equal to the longer central line of floater is defined 0 degree and the positive angle direction is calculated anticlockwise. In the experiment, 45,60 and 90 degree was employed as the wave principal direction. The model elasticity of the floater is reproduced in a board with aluminum plate and polyurethane panel. The difference in elasticity from the target was smaller than 10%.

The countermeasure system against the vertical motion and the wave reflection is made from numerical triangle slit members 5m width and 7m high. The upper and lower edges of member were attached on the face of pontoon. The opening space of slits was 20% in average. We compared the effect of horizontal plate 4m wide in the experiment.

Figure 9 shows the model outline employed in the experiment. Fig.9(1) and (2) represents the cross and overview of horizontal plate and wave dissipating slit members respectively. In the experiment, the vertical displacement of representative measurement point and mooring tension were compared in the case of pontoon floater without any countermeasure and with the countermeasures (plate and slit members). In the model experiment, slit members are made from plastic rectangular bars. The wave energy is expected to be absorbed inside the triangle slits due to wave braking and turbulences.

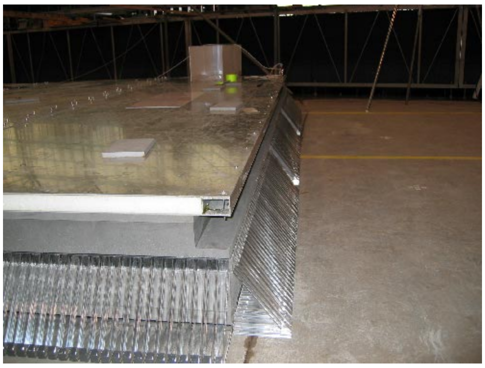


(1) Horizontal board system



(2) Slit type wave absorber system

Figure 9 Attachment to reduce vertical motion of pontoon floater



Photograph 2 Overview of model slit member to dissipate wave energy

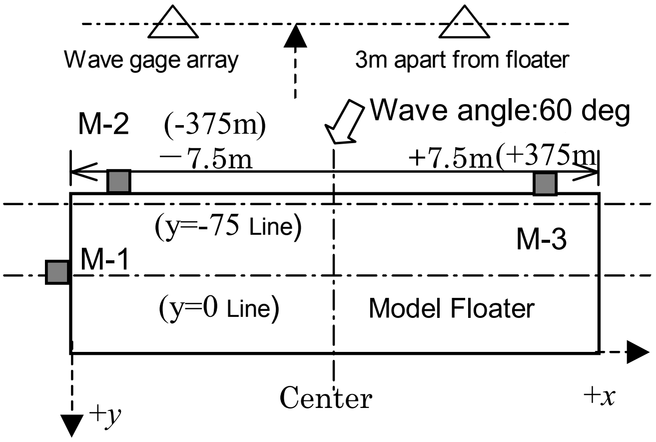


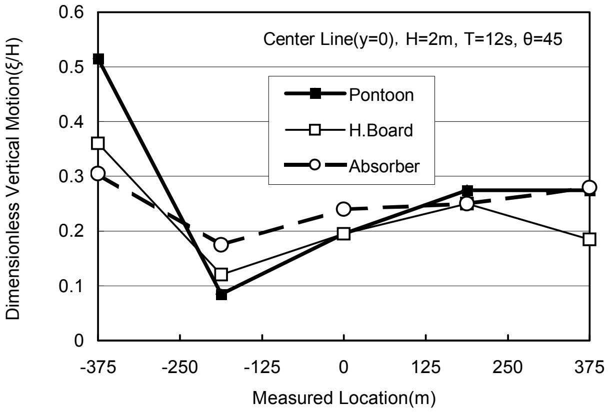
Figure 10 Arrangement of tension meter

Photograph 2 shows the cross view of model slit members attached on the pontoon side walls.

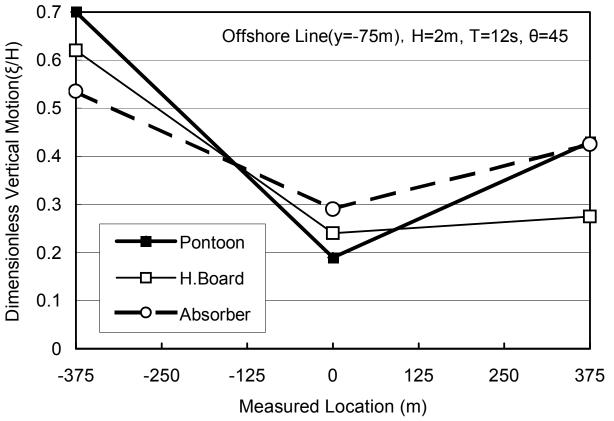
Figure 10 shows the arrangement of measurement lines employed in the comparison test. The line (*y*=-75) represents the line with three reflectors for Laser displacement sensors and the line (*y*=0) with five laser reflectors. The M-1, M-2 and M-3 points represent the location of spring mooring line connected with the tension meters. The obtained mooring tension is converted using the regular wave drift force expressed by Eq.(1).

Figure 11 shows the comparison of vertical dimensionless displacement obtained in side measurement line (*y*=0) when the wave angle becomes 45 degree. The vertical displacement of pontoon type floater becomes remarkable in downstream side for wave incident (*x*=-375m). The maximum vertical displacement at *x*=-375m became 50% of incident wave height. The vertical displacement in the downstream side (*x*=-375m) became smaller in case of improved pontoon attached with the horizontal plate and wave dissipating slit members. Fig.11(2) shows the displacement obtained in the side line (*y*=-75m). The displacement in the downstream side for incident wave becomes 0.7 in normal pontoon, 0.6 in horizontal plate and 0.52 in wave dissipating slit members.

Figure 12 shows the comparison of vertical displacement at the downstream side (x=-375m, y=-75m) where the amplitude becomes the maximum. The dimensionless displacement increases as the wave period increase and the wave angle closes to 90 degree. The effects in countermeasure system become significant when



(1) On center line of floater (y=0)



(2) On offshore side line of floater (y=-75)

Figure 11 Spatial variation of dimensionless vertical motion for different floater attachment

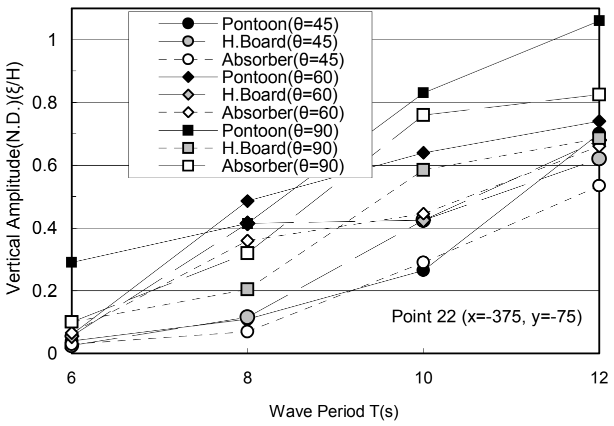


Figure 12 Reduction of vertical displacement amplitude in countermeasure system

the wave period increase and wave angle closes to 90 degree. The difference in the vertical displacement between the normal pontoon, horizontal plate and wave dissipating slit becomes small when the incident wave angle is 45 degree. Therefore the countermeasure system becomes more effective in case that the waves act on pontoon floater in the angle of 60 to 90 degree.

Figure 13 shows the comparison of dimensionless displacement in the horizontal plate and wave dissipating slit members in case of wave angle =90 degree and H=4m. The dimensionless vertical displacement in horizontal plate system becomes smaller than in the wave dissipating slit systems. The horizontal plate is superior to the slit member system under consideration of reduction of pontoon motion.

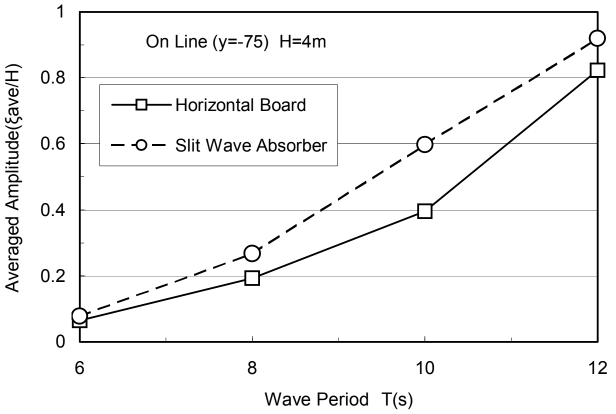


Figure 13 Effect of improved wave absorbing slit members

Figure 14 shows the comparison of vertical displacement obtained in directional wave with the wave principal direction of 60 degree. The vertical axis corresponds to the maximum and significant displacement amplitude divided in the significant wave height. The difference of the dimensionless vertical amplitudes (the two cases of horizontal plate and wave dissipating slit members), becomes small. In the significant amplitude, the differences are very small. The differences between the both systems are smaller than 10%. The wave dissipating slit members make the displacement reduction effect similar to the horizontal plate.

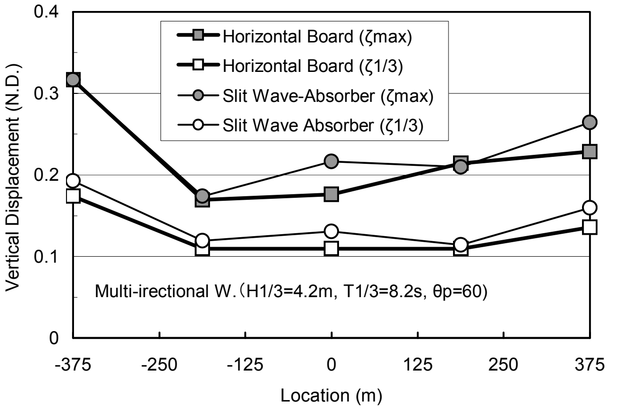
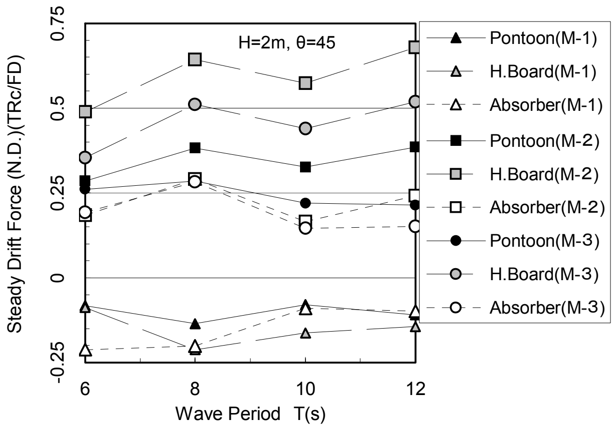


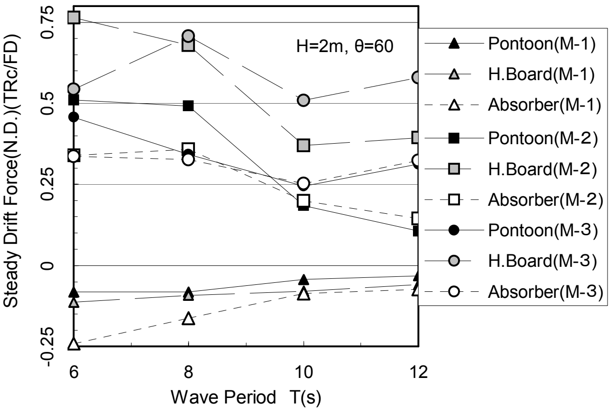
Figure 14 Floater motion in directional waves

5.3 Variation of mooring tension

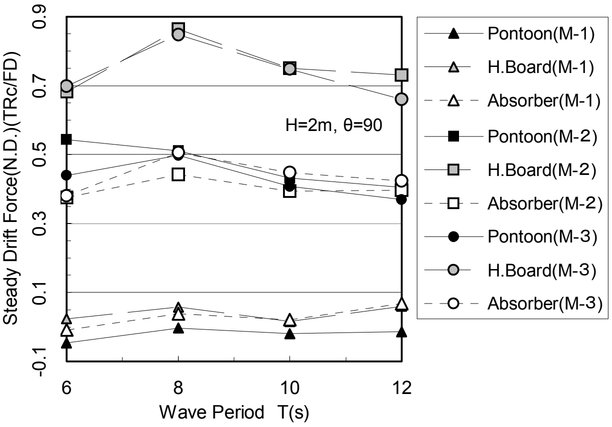
Figure 15 shows the comparison of dimensionless mooring tension induced in the drift force due to regular waves. Fig.15 (1), (2) and (3) represents the variation of dimensionless mooring tension in case of wave angle of 45, 60 and 90 degree respectively. The sensor on M-1 measures the tension acting parallel to the long central line of floater. The side sensors indicated in M-2 and M-3 are attached on the side face of floater and the both mooring lines fix the location of floater and mainly correspond to the wave drift force. In the all cases indicated in the figures, the dimensionless tension in the horizontal board case become larger than those in pontoon and wave dissipating slit members. In case of wave angle = 45 degree, the mooring tension acting on M-2 becomes about two times larger in the horizontal plate than in the normal pontoon.



(1) in case of $\theta = 45$d.



(2) in case of $\theta = 60$d.



(3) in case of $\theta = 90$d.

Figure 15 Variation of mooring tension due to steady wave drift force in regular wave action

The design of mooring system becomes remarkable difficult when the mooring tension becomes two times larger than in the normal case. Meanwhile the tension obtained in the wave dissipating slit members becomes slightly smaller than in the normal pontoon type. In case of oblique wave cases given in Fig. 15 (2) and (3), the mooring tension in wave dissipating slit members become almost equal to the tension acting on the normal pontoon. Therefore the wave energy dissipating slit member system is superior to the horizontal plate system as the mooring tension due to drift force become much smaller.

Figure 16 shows the comparison of dimensionless mooring tension components obtained in case of directional random waves. The tension obtained in M-2 and M-3 is averaged and divided into the stable and oscillating components. The stable component *Trc* derived from the irregular mooring tension corresponds to the wave drift force and oscillating *Trs* the slowly oscillating wave drift force. In the figure the maximum *Trsmax* and significant slowly wave drift force *Trs1/3* is compared. The difference between the stable drift forces obtained in the horizontal plate and wave dissipating wave slit members cases is smaller compared in case of the slowly oscillating wave drift force. The amplitude of slowly varying wave drift force is much larger than the amplitude of stable drift force and the slowly varying component becomes important to the design of mooring structures. Therefore the wave dissipating slit member system is more applicable as the displacement reducer for large pontoon type floater in directional wave states.

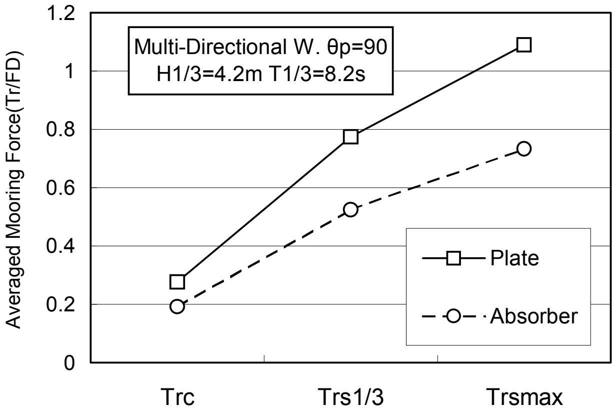


Figure 16 Variation of mooring force for floater type

5.4 Variation of wave reflection

Figure 17 shows the variation of wave reflection coefficient derived in the wave gage array installed offshore the pontoon floater. The figure shows the variation of wave reflection coefficient for regular wave period. The wave reflection coefficient becomes larger than 0.6 in case of the normal floater without any displacement reducers. When wave period become shorter than 8s, the wave reflection coefficient obtained in the displacement reducers becomes very small and less than 0.4. The difference of reflection coefficient among the three type floater becomes small when wave period increases. However the reflection coefficient in the horizontal board and wave dissipating slit members becomes smaller than the reflection coefficient in the normal pontoon.

The wave energy dissipating slit members is applicable to the practical vertical displacement reducers because the mooring tension is not amplified and the reflection coefficient becomes smaller than in the normal pontoon floater.

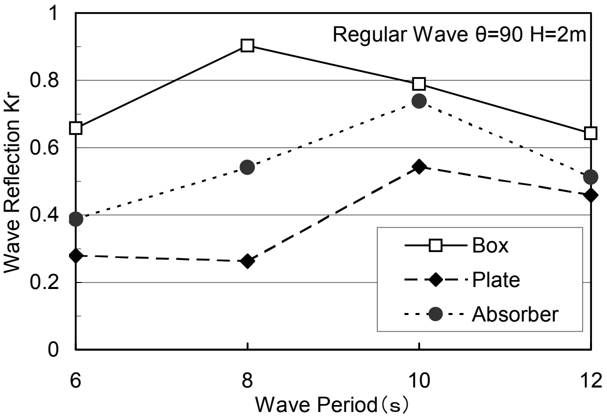


Figure 17 variation of wave reflection coefficient for floater type

6. Conclusions

The floater model with 1/50 scale was installed in a directional wave basin to obtain the variation of vertical displacement including the heaving, rolling and pitching motions and the mooring tension. The three types of floaters (Pontoon, Semi-sub and Combination) were employed in the three dimensional model test.

In the experiment, the motion of pontoon type was revealed to be larger than the other types. The countermeasure system to reduce the vertical motion is proposed and investigated in the later part of the paper. The counterpart of vertical motion proposed here is the triangle slit members attached on the pontoon floater.

The following results are derived;

1) The vertical motion of the pontoon type floater becomes larger in the multi-directional waves than in the uni-directional. Meanwhile the motion of the semi-sub type floater has the inverse tendency.
2) The vertical displacement distribution of combination type floater becomes similar to that of pontoon type even in the semi-sub floater component area.
3) The amplitude of vertical motion of combination type floater approaches to that of pontoon type floater when the wave period increases for case of regular waves.

4) The mooring tension acting the pontoon and combination type floater becomes larger in the multi-directional waves than in the uni-directional in case of the principal wave directional of 90 degree. The significant tension in the multi-directional waves becomes similar to that in the uni-directional in case of oblique principal wave direction. The employment of multi-directional wave is important to the design of mooring systems in real sea conditions.
5) The newly proposed slit members are able to reduce the vertical motion of the pontoon type floater.
6) The mooring tension for the floater with the slit type wave absorber does not increase while the tension of the floater with a horizontal plate become larger than the normal pontoon type floater.
7) The wave reflection coefficient of floater with the slit members becomes less than 0.6 when the wave angle is 8 and 12s.

The paper demonstrates the importance of multi-directional wave experiment for the large elastic floater. The other main conclusion is applicability of the slit type wave absorber to reduce the vertical motion. Finally the authors express a sincere thanks to Dr. Shunji Kato, Head of Ocean Space Utilization Group, Ocean and Ice Engineering Department, National Maritime Research Institute for his kind suggestion to the experimental results.

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Symbols

C_{ds}	:	Wave drift force coefficient
F_{RD}	:	Wave drift force
$H_{1/3}$	:	Significant wave height
K_r	:	Wave reflection coefficient
L_a	:	Total length of floater
$T_{1/3}$	:	Significant wave period
T_{rc}	:	Mooring tension due to steady wave drift force
T_{rs}	:	Mooring tension due to slowly oscillating wave drift force
WD	:	Incident wave direction
Z or ζ	:	Vertical Displacement
η	:	Water level
ρ	:	Water density

港湾空港技術研究所資料　No. 1151

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