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PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
UNIVERSITY OF ICELAND
DEPARTMENT OF ENGINEERING AND SCIENCE

DEEP WATER MOORED SEMI-SUBMERSIBLE PLATFORM - THEORY AND MODEL TESTS

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INTRODUCTION

Any object freely floating at sea has six degrees of freedom. This is true also for drillships and offshore floating platforms moored conventionally or by dynamic positioning. A concept introduced by J.R. Paulling and E.E. Horton (11) reduced the motion of a platform to three degrees of freedom by applying vertical prestressed cables anchoring the platform to the sea bottom.

To obtain tension in the cables under all wave conditions the static buoyancy must exceed the maximum dynamic force variation in the cables caused by wave action. The triangular platform is anchored in its three corners giving a statically determinate system. The proposed design is in particular suitable for large water depths.

This paper is based on a master thesis at the Division of Port and Ocean Engineering in 1972. Forces in the anchor cable and the horizontal movement (surge) for three different platforms were investigated theoretically and by model tests. Fig. 1 gives a flow-diagram for the investigation in regular waves.

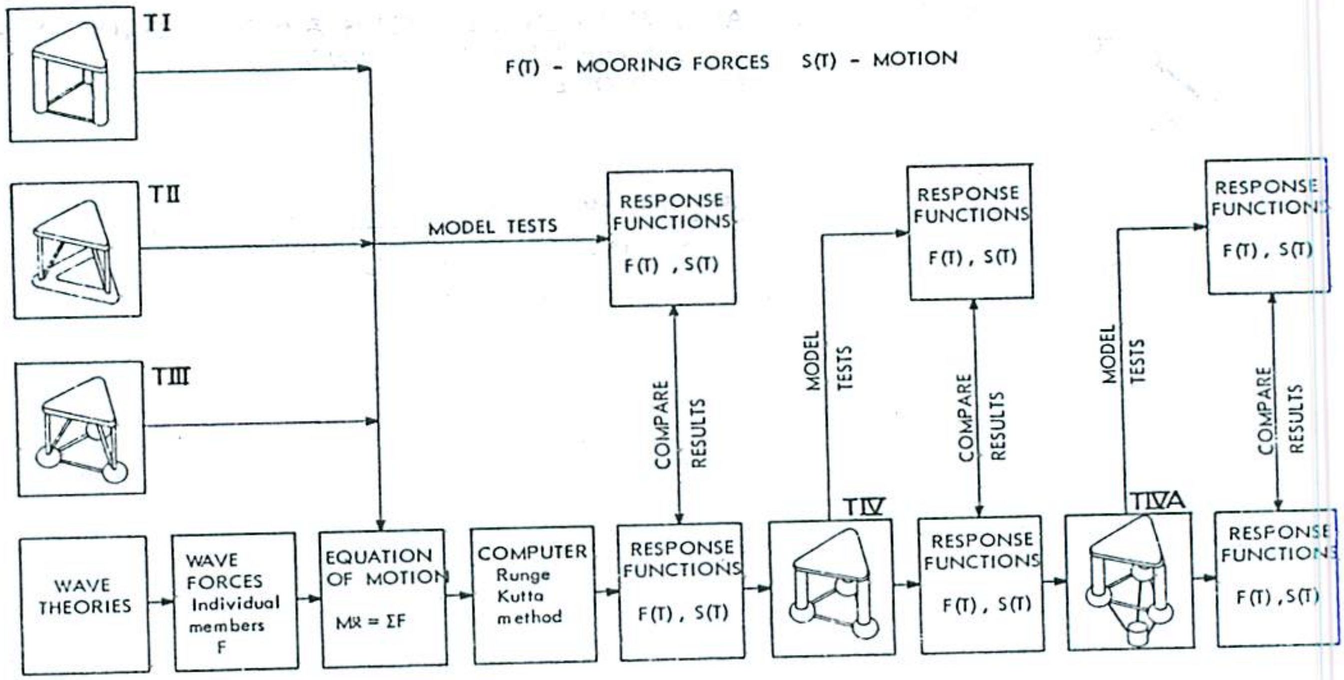


FIG. 1. FLOW DIAGRAM REGULAR WAVES

Three main types of buoyancy systems were investigated in the star
to check different design principles. One type (T I, Fig. 1) with
vertical cylinders piercing the sea surface, another type (T II)
with horizontal submerged cylinders and the third type (T III) wit
submerged spheres. All other submerged or semi-submerged members
the platform were made as small as possible only securing a rigid
construction.

To reduce the dynamical mooring forces a new platform, T IV, was d
signed combining the characteristics of the platforms T I and T II
The design was based on the criteria of minimizing the vertical wa
forces on the platform for a period close to the peak period in ar
actual wave spectrum. Finally T IV A was provided with a stabili
minimizing the dynamical mooring forces caused by the different lc
tion of the resultant of the horizontal wave forces and the cente
gravity of the platform.

The model tests were run in scale 1:200. Most of the tests were r
in regular waves. For the final platform design some tests were c
ducted in irregular waves checking the transfer function concept
regular waves.

Realistic platform parameters were aimed at based on a literature survey. The following prototype data were chosen for the platforms:

Weight under operation	10 000 t
Total buoyancy	14 500 t
Cable pretension (in each)	1 500 t
Triangle side length	80 m
Deck level above SWL	18 m
Weight in light condition	6 000 t
Metacentric height	10 m

FORCES ON THE PLATFORM

The theoretical analyses are based on linear wave theory and the following assumptions:

a. As the platform members are small compared to the wave length the incident wave is considered undisturbed by the members.

b. The hydrodynamic interaction effects between neighbouring members of the platform is neglected.

The velocity potential for regular waves moving in the direction of the positive x-axis is given as (Fig. 2):

$$\phi = - \frac{\mu_1 \, g \, H}{2 \, \omega} \cos(\omega t - kx) \qquad (1)$$

where

$\mu_1 = \dfrac{\cosh k\,(h+z)}{\cosh kh}$

g = acceleration of gravity

ω = circular frequency of wave oscillations = $\frac{2\pi}{T}$

k = wave number = $2\pi/L$

h = water depth

T = wave period

L = wave length

H = wave height

The water particle velocities and accelerations are derived from equation (1).

In x-direction:

$$u = -\frac{\partial\phi}{\partial x}, \qquad \dot{u} = \frac{\partial u}{\partial t} = -\frac{\partial^2\phi}{\partial x \partial t}$$

In z-direction:

$$v = -\frac{\partial\phi}{\partial z}, \qquad \dot{v} = \frac{\partial v}{\partial t} = -\frac{\partial^2\phi}{\partial z \partial t}$$

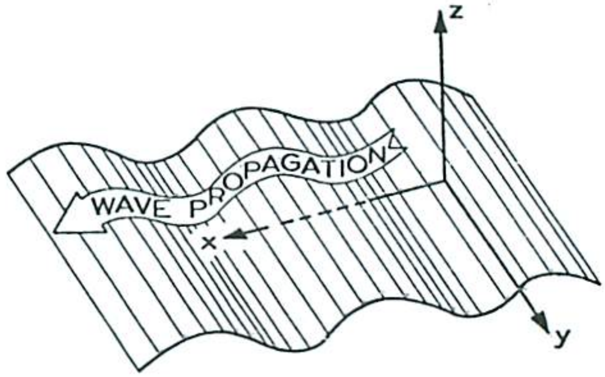


FIG. 2 DEFINITION SKETCH

Wave forces

Considering the motion between the water particles in the wave relative to the platform, the total horizontal wave force on each member can be expressed as:

$$F_x = F_P + F_{AM} + F_D$$ (2

where:

$$F_P = \rho\ V\ \dot{\bar{u}}$$ (3

the undisturbed pressure force

$$F_{AM} = C_m\ \rho\ V\ (\dot{\bar{u}} - \ddot{x})$$ (4

the added mass force due to the presence of the member

$$F_D = 0.5\ \rho\ C_D\ A\ (\bar{u} - \dot{x})|\bar{u} - \dot{x}|$$ (5

the damping force due to viscous effects

V = submerged volum of the menber

A = projected area of the member

ρ = water density

C_m = added-mass coeffisient

C_D = drag-coeffisient

$\dot{u}$, $\bar{u}$ = the water particles accelerations and velocities averaged over the submerged volume. See table 1

$\ddot{x}$, $\dot{x}$ = accelerations and velocities of the platform in the x-direction

The total vertical wave force, F_z, can be expressed in a similar way as F_x changing the accelerations and velocities to z-direction ($\dot{v}$,v).

Table 1 gives the expressions for the average velocities and accelerations on a vertical and a horizontal member. The theoretical calculations neglect the inclined small members.

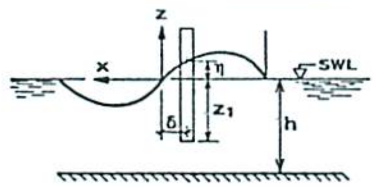
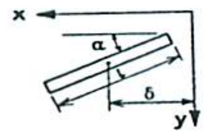
	VERTICAL MEMBER	HORIZONTAL MEMBER
		
HORIZONTAL DIRECTION	$\bar{u}_z = K_2 \frac{\omega H}{k(\|z_1\|+\eta)2} \sin(\omega t-\delta-kx)$	$\bar{u}_x = K_1 \; \omega \; H/2 \; \mu_3 \; \sin(\omega t-\delta-kx)$
	$\bar{\dot{u}}_z = K_2 \frac{\omega^2 H}{k(\|z_1\|+\eta)2} \cos(\omega t-\delta-kx)$	$\bar{\dot{u}}_x = K_1 \; \omega^2 \; H/2 \; \mu_3 \; \cos(\omega t-\delta-kx)$
VERTICAL DIRECTION	$\bar{v}_z = K_3 \frac{\omega H}{k(\|z_1\|+\eta)2} \cos(\omega t-\delta-kx)$	$\bar{v}_x = K_1 \; \omega \; H/2 \; \mu_2 \; \cos(\omega t-\delta-kx)$
	$\bar{\dot{v}}_z = K_3 \frac{\omega^2 H}{k(\|z_1\|+\eta)2} \sin(\omega t-\delta-kx)$	$\dot{v}_x = -K_1 \; \omega^2 \; H/2 \; \mu_2 \; \sin(\omega t-\delta-kx)$

TABLE 1 AVERAGE VELOCITIES AND ACCELERATIONS

where:

$$K_1 = \frac{2 \sin(0.5 \; k \; l \; \cos\alpha)}{k \; l \; \cos\alpha}$$

$$K_2 = \frac{\sinh k(h+\eta) - \sinh k(h+z_1)}{\sinh kh}$$

$$K_3 = \frac{\cosh k(h+\eta) - \cosh k(h+z_1)}{\sinh kh}$$

Mooring forces

The mooring force, F_m, in each cable can be determined by simple static analysis from Fig. 3.

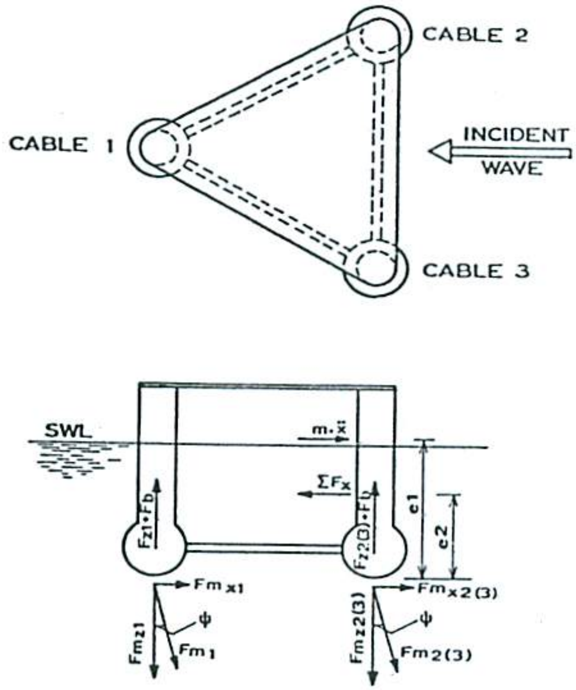


FIG. 3 FORCES ON THE PLATFORM

$$F_{m_1} = \frac{1}{\cos\psi}\left(-\frac{m\ \ddot{x}\ e_1 - \Sigma F_x\ e_2}{\ell} + F_{z_1} + F_b\right) \tag{6}$$

For cable 2 and 3:

$$F_{m_{2\,(3)}} = \frac{1}{\cos\psi}\left(\frac{m\ \ddot{x}\ e_1 - \Sigma F_x\ e_2}{2\ \ell} + F_{z_{2\,(3)}} + F_b\right) \tag{7}$$

where:

$F_{z_{1\,(2)\,(3)}}$ = vertical wave forces on the members that influence the respective cables

F_b = net boyancy = $1/3\ (\rho\ \Sigma V - mg)$

The horizontal component of the mooring force follows from:

$$F_{m_x} = F_m \sin\psi \approx F_m \frac{x}{s} \tag{8}$$

where:

x = the horizontal displacement of the platform

s = the cable length

EQUATION OF MOTION (SURGE)

When all the external forces acting on the platform are determined the equation of motion is derived from Newton's second law:

$$m \ddot{x} = \Sigma F = \Sigma F_x - \Sigma F_{m_x} \tag{9}$$

This equation has no analytic solution for two reasons:

1. The expressions for ΣF_{m_x} will give terms like $\ddot{x}$ x (equation 6-7-8)

2. The average accelerations and velocities are determined for the instantaneous position of the wave relative to the individual member

   $\bar{u}$ = function of $\cos(\omega t-\delta-kx)$

   $\bar{\dot{u}}$ = function of $\sin(\omega t-\delta-kx)$

where:

δ = the members equilibrium position from the origin in the coordinate system

x = the platform (and thereby the members) surge displacement

The equation of motion was solved numerically using computer and standard numerical integration methods. In this case the method of Runge - Kutta was used.

The configuration of the platforms and moorings used in the computer program were approximated to each model configuration. The greatest uncertainty was in the selection of hydrodynamic coefficients. Selection of the added mass coefficient, C_m, was based on values calculated from potential flow theory (10), neglecting free surface effects. The selection of the drag coefficient, C_D, was based on available data from steady state flow. The following coefficients were used:

cylinder: $C_m = 1.0$, $C_D = 0.6$

sphere: $C_m = 0.5$, $C_D = 0.4$

The computer program gave the following output as a function of time:

a) the wave profile

b) the horizontal movement (surge) velocities and accelerations of the platform (x, $\dot{x}$, $\ddot{x}$)

c) the horizontal and vertical wave forces

d) the mooring force in each cable

e) the natural surge frequency

MODEL TESTS REGULAR WAVES

Model tests in regular waves were run in a flume at the River and Harbour Laboratory. Model scale 1:200. Wave flume dimensions:

Width	5 m
Length	54 m
Waterdepth	1 m

The model was placed 30 m from the wave generator.

During the model tests wave parameters corresponding to the followin prototype waves were used:

Wave periods	8.5 - 25 sec
Wave heights	4 - 24 m

Fig. 4 shows a schematic drawing of the test arrangement. The parameters recorded were:

1. The surge motion of the platform.
2. The tension force variations in the mooring cables.
3. Wave parameters at the same position from the wave flap as the platform.

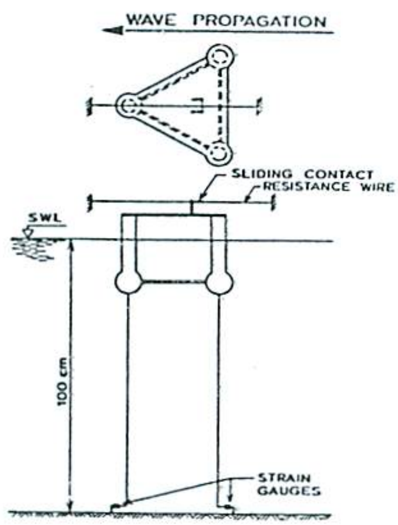


FIG. 4 TEST ARRANGEMENT

The surge motion was measured by a sliding contact on a resistance wire. Forces in the mooring cables were measured by strain gauges mounted at the bottom of the flume and the wave parameters by ordinary resistance wave gauges.

The results were recorded on paper charts with the possibility of varying the paper speed thus enabling a check on the phaselag for the different registrations.

All model data were converted to prototype conditions according to Froudes model law where friction and surface tension forces are neglected. With a model scale of 1:200 some scale effects, however, must be expected.

The incident wave direction was kept constant relative to the platform position as shown on Fig. 4.

RESULTS IN REGULAR WAVES

The theoretical results were compared to the model test results converted to prototype conditions. For a specific wave period the parameters show an approximate linear variation with the wave height, hence the results are presented in response functions.

The relative importance of the different forces was investigated in the computer program. Inertia force dominated entirely. The horizontal mooring force component was of the same order of magnitude as the drag force. Maximum values of these two forces were less than five percent of the maximum inertia force.

A comparison of the inertia force integrated to SWL and to the actual wave profile showed very little difference in variation of the forces. As the maximum acceleration occurs at SWL, the integration of the inertia force was carried out to this level.

The influence of the pretension in the mooring cables was tested theoretically on design T I assuming different values for the diameter of the vertical boyancy cylinders. The results showed little effect of the pretension in the cables. An increased pretension caused a slightly higher force variation which might be expected as the submerged volume was increased.

Fig. 5 shows the dynamical mooring force variation for platform T I - T III as a function of wave period. The force variation is given as the peak to peak value per meter waveheight.

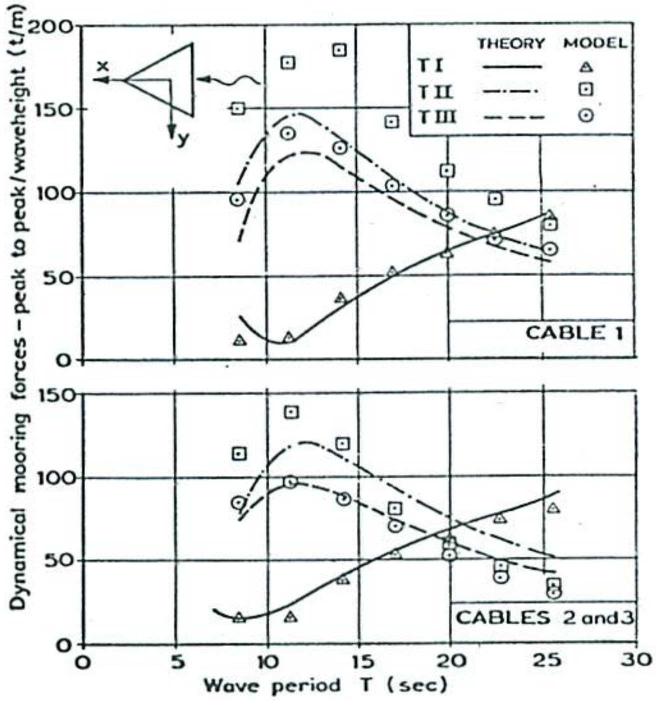


FIG. 5 MOORING FORCES. RESPONSE FUNCTIONS
REGULAR WAVES (T I - T III)

The theoretical and experimental values show a reasonable agreement. The poorest fit is found for T II where the model tests gave up to 30% higher values than the theoretical results. A possible explanation for this is that members in this boyancy system interfere with each other.

Fig. 6 is an example of the model test records for a wave period of 11.3 seconds and 16 m waveheight. The figure shows the phase lag between the different recorded parameters.

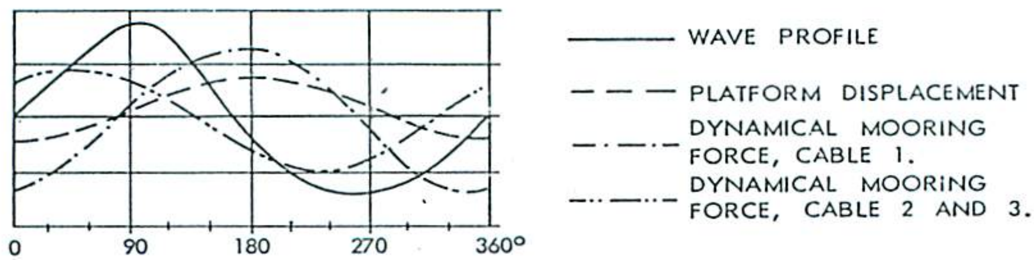


FIG. 6 MODEL TEST RECORDS

For wave periods of 15 - 16 seconds the total surge motion (peak to peak) was about equal to the waveheight. When the wave period increased the surge motion increased, too. At 25 - 27 seconds the total surge equalled twice the wave height.

The design of T IV was based on the theoretical and experimental results of T I - T III, minimizing the vertical wave forces for a wave period of 14.1 seconds corresponding to the peak period in the design wave spectrum chosen.

The undisturbed vertical pressure force on a submerged and floating structure is 180 degrees out of phase. When in addition the vertical added mass force on the vertical cylinders is neglected, the boyancy systems of T I and T III may be combined giving a design, T IV, with zero resultant vertical wave force for a given wave period.

The remaining dynamical mooring forces are caused by a moment due to excentricity between the total horizontal wave force (ΣF_x) and the inertia force ($m\ddot{x}$). Ref. Fig. 3 and equation 6 and 7. By applying a stabilizer under the platform a corresponding moment directed opposite is introduced. An open vertical cylinder is used which is rigidly connected to the platform. The cylinder is open because this causes negligible vertical forces and high inertia forces in the horizontal direction.

The diameter of the cylinder is chosen taking into consideration that the drilling should not be hindered under any reasonable weather condition. The length of the cylinder is then given by simple equilibrium moment considerations.

The platform design with the stabilizer is called T IV A and the main dimensions are given in Fig. 7.

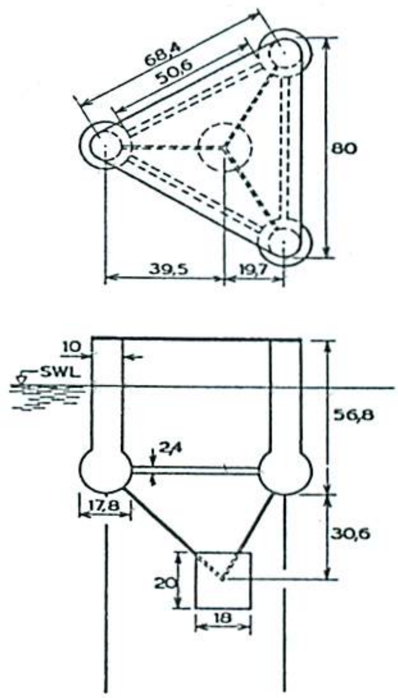


FIG. 7 T IV A MAIN DIMENSIONS IN METERS

Fig. 8 shows the surge response functions for T IV and T IV A. The surge motion is reduced by 15 - 25 percent when using the stabilizer design.

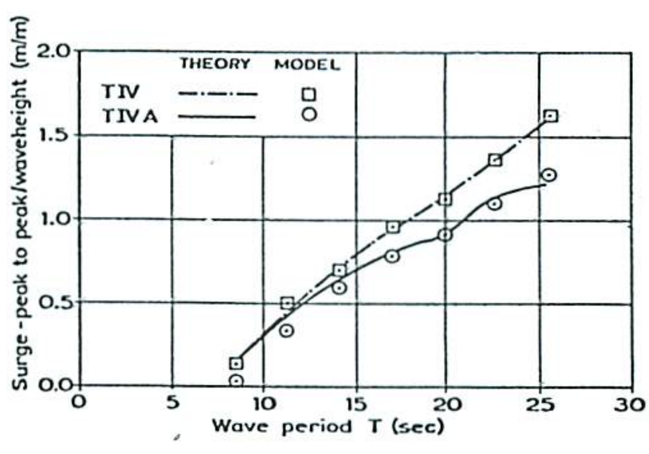


FIG. 6 SURGE RESPONSE FUNCTIONS
REGULAR WAVES

The response functions for the mooring forces are shown in Fig. 9.

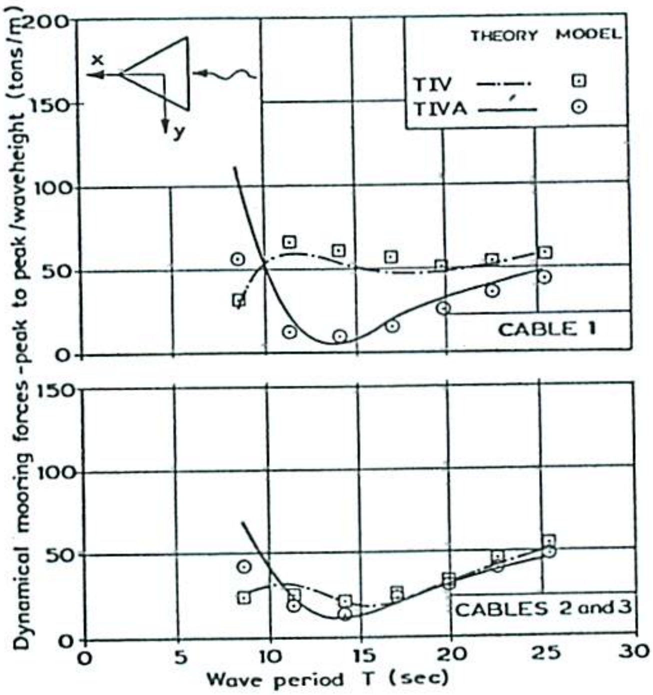


FIG. 9 MOORING FORCES. RESPONSE FUNCTIONS REGULAR WAVES

The figure shows clearly that the stabilizer is most effective for the design wave period. The dynamical force variations are reduced and the cable pretension may be reduced accordingly.

For periods less than 10 - 11 seconds the force response functions rapidly increase with decreasing wave periods. The reason for this may be explained from Fig. 10.

For waves with periods of 13 - 14 seconds or more the surge movement of the platform is about 90 degrees out of phase with the wave profile. Fig. 10 a gives variations in moment for the design period together with the resulting dynamical mooring force in cable 1. Periods less than about 10 seconds give wavelengths relative to the platform size that cause another phase-lag between platform and wave. Fig. 10 b shows the conditions for a wave period of 8.5 seconds. The phase-lag between platform and wave in this case changed to about 60 degrees, causing variations in moments with phase-lags different from those given in Fig. 10 a. For part of the wave period the moments all acted in the same direction resulting in a higher dynamical mooring force in cable 1.

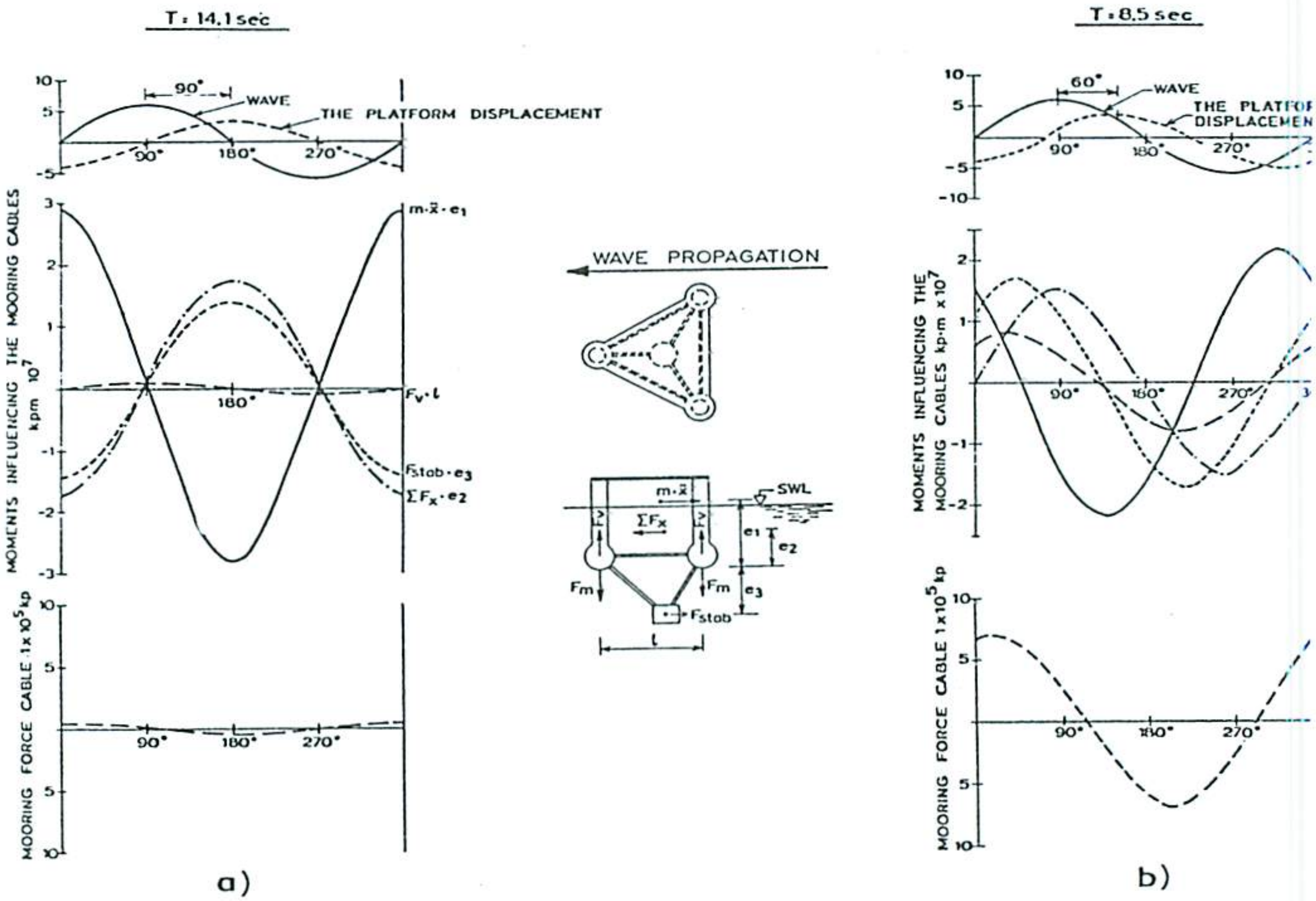


FIG. 10 PHASE-LAGS FOR PERIODS 14.1 AND 8.5 SECONDS

Differences between theoretical and experimental results for peri less than about 10 seconds (Fig. 9) are possibly caused by the sensitivety for small changes in the phase-lag or it may be a sca effect.

The unfavourable theoretical response function for shorter wave periods could possibly be improved by one or more of the followin suggestions:

1. Optimization of the stabilizer for a lower wave period.
2. Making the stabilizer depth adjustable by varying the length of the rigid connections.
3. Changing the volume of the stabilizer by:

a) making the cylinder telescopic

b) using two adjacent slotted cylinders with adjustable slotting areas

One must also bear in mind that although response functions increase, maximum waveheight will decrease for decreasing wave period. By proper choice of the optimization period it should be possible to keep the mooring forces within an acceptable level.

THE PLATFORM IN IRREGULAR SEA

So far the motion of the platform and the mooring forces were only investigated as functions of time for regular waves. For a given irregular sea state design parameters (for instance the motion of the platform and the mooring forces) should not exceed a value set by consideration to safety and working conditions.

For linear systems transfer functions may be used. The response function in irregular sea results by combining the transfer function in regular sea with the actual irregular wave spectrum:

$$\phi(f) = TF^2(f)\ E(f) \tag{10}$$

where:

$\phi(f)$ = Response spectral density
$TF(f)$ = Transferfunction, regular waves
$E(f)$ = Wave spectral density

The total energy of a response function over the whole frequency range is determined by:

$$m_o = \int_o^\infty \phi(f)\ df \tag{11}$$

Assuming that wave heights are Rayleigh distributed the following relation between the significant value ϕ_{13} and m_o exsist:

$$\phi_{1/3} \approx 4\ \sqrt{m_o}$$

Model tests in irregular waves for T IV and T IV A were conducted and the results compared to those obtained by the above mentioned concept (Fig. 11).

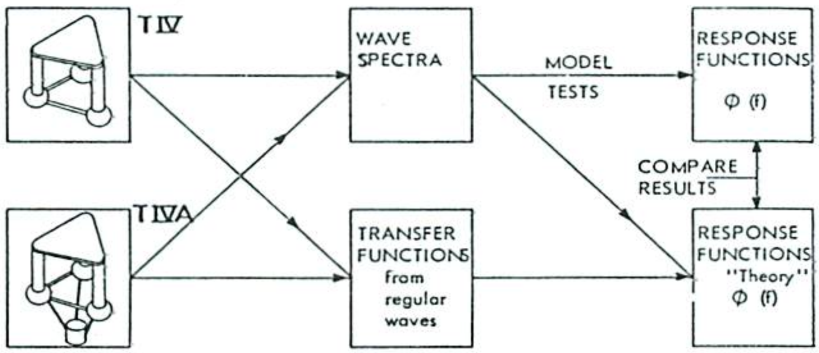


FIG. 11 FLOW DIAGRAM, IRREGULAR WAVES

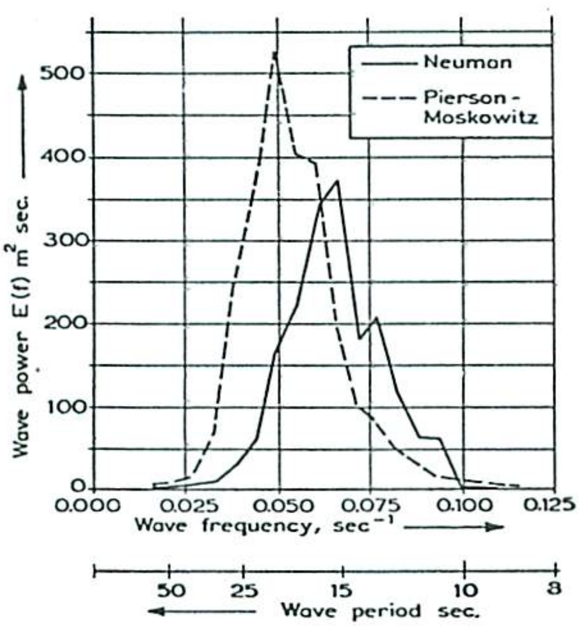


FIG. 12 WAVE SPECTRA

Two wave spectra shown in Fig. 12 were used. The Neuman wave spectrum had a peak period of about 15 seconds or close to the design wave period chosen for the platform. The Pierson Moskowitz spectrum had a peak period around 20 seconds.

Results in irregular waves

Figs. 13 and 14 show the response functions for mooring forces and surge motion respectively, for the Neuman wave spectrum.

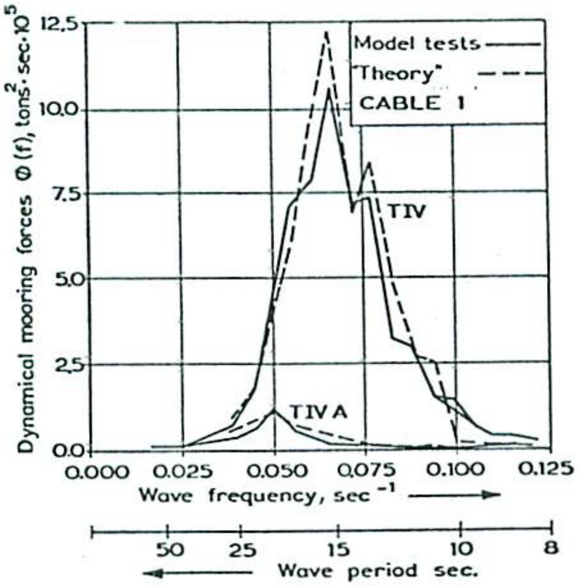


FIG. 13 MOORING FORCES $\phi(f)$
RESPONSE FUNCTIONS
IRREGULAR WAVES
(Neuman)

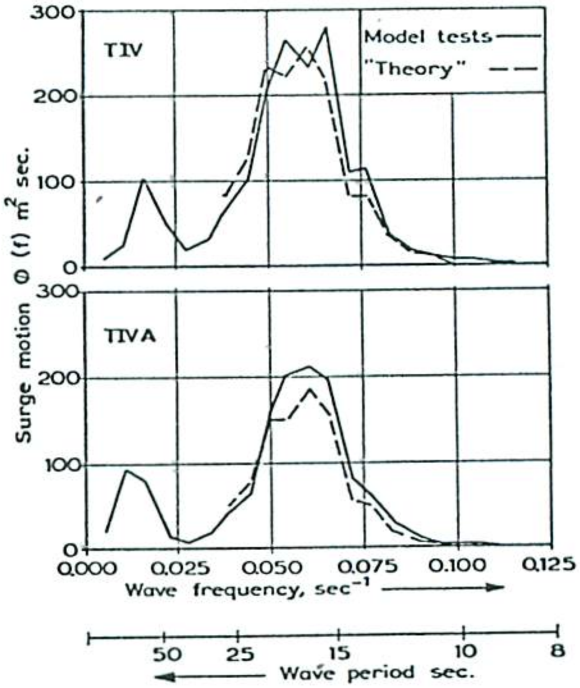


FIG. 14 SURGE RESPONSE FUNCTIONS
IRREGULAR WAVES
(Neuman)

The transfer function concept seems valid in this case. Figs. 13 and 14 show good agreement between "theory" and model tests. The effect of the stabilizer on the mooring forces may be seen in Fig. 13. The Pierson-Moskowitz spectrum which has a higher peak period showed a similar trend with a smaller reduction of the mooring forces than for the Neuman spectrum. Table 2 gives the significant values for the mooring forces in cable 1 and surge motion for the two spectra.

			T IV				T IV A			
			THEORY		MODEL		THEORY		MODEL	
	$H_{1/3}$ (m)	T_{peak} (s)	$F_{1/3}$ (t)	$S_{1/3}$ (m)	$F_{1/3}$ (t)	$S_{1/3}$ (m)	$F_{1/3}$ (t)	$S_{1/3}$ (m)	$F_{1/3}$ (t)	$S_{1/3}$ (m)
NEUMAN	13.0	≈15	735	11.8	722	11.6	205	8.9	184	9.1
PIERSON-MOSKOWITZ	13.0	≈20	744	16.1	708	16.0	347	12.8	389	13.1

TABLE 2 SIGNIFICANT MOORING FORCES AND SURGE

THE ACCELERATION OF THE PLATFORM

The acceleration of the platform is of great importance for workin conditions onboard. The literature available is mainly concerned with the effect of high-frequency oscillations on man, while the movement of the platform is in the low-frequency range. Different acceptable levels have to be applied for high- and low frequency oscillations.

The acceleration of the platform, $\ddot{x}$, is given in the computer outp when solving the equation of motion. Fig. 15 shows the results fo T IV.

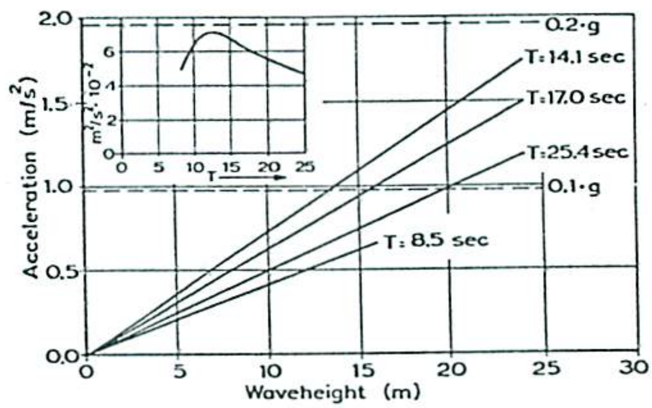


FIG. 15 PLATFORM ACCELERATION T IV

For passenger ships the "comfort limit" for horizontal oscillatio is given as 0.4·g. For high-frequency oscillation 0.1·g is an acceptable level. According to Fig. 15 a design wave of T = 14 s H = 24 m gives an acceleration of 0.17·g, which probably should be acceptable for this type of oscillation.

CONCLUSIONS

1. The theoretical and experimental results show good agreemen indicating that the assumptions made are valid and that the hyd dynamical coefficients are chosen properly. Scale effects sho however, be taken into consideration when comparing the theoret and experimental results.

2. The total drag force on the platform due to the waves was found to be negligible compared to the inertia forces. The hor zontal component of mooring forces has the same order of magnit

as the drag force. Thus the main mooring effect is to keep the platform in translational motion.

3. The pretension in the mooring cables has only little effect on the dynamical mooring forces caused by wave action.

4. The results from the investigation show that platform geometry is of great importance for the dynamical mooring forces. Combining different design principles desired characteristics may be obtained by theoretical computations.

5. The stabilizer was very effective for the chosen optimization wave period. Shorter wave periods changed the phase-lags causing the response function to increase.

6. Although it has not been investigated, equations 6 and 7 show that an another way to reduce the dynamical mooring forces is to increase the side length of the platform.

ACKNOWLEDGEMENT

The investigation was carried out under the supervision of Dr.techn. P. Bruun. The computer program was run at the Computing Center and the model tests conducted at the River and Harbour Laboratory at the Norwegian Institute of Technology. We also highly appreciate the help of Mr. I. Sætereng during the model tests.

NOMENCLATURE

A	=	projected area of a member
C_m	=	added mass coefficient
C_D	=	drag coefficient
$E_{(f)}$	=	wave spectral density
F_x	=	total horizontal wave force on each member
F_v	=	total vertical wave force on each member
F_{AM}	=	added mass force
F_D	=	drag force
F_b	=	net buoyancy = $1/3(\rho\ \Sigma V - mg)$
$F_{m_{1(2)(3)}}$	=	mooring force in the respective cables 1, 2 and 3
F_{m_x}, F_{m_z}	=	horizontal and vertical component of F_m

F_p = the undisturbed pressure force (Froude-Kriloff force)

g = acceleration of gravity

h = water depth

H = wave height

k = wave number = $2\pi/L$

L = wave length

m = platform mass

m_o = total energy of response function

s = cable length

T = wave period

$TF(f)$ = transfer function

u, $\dot{u}$ = velocity and acceleration of water particles in x-direction

$\bar{u}$, $\bar{\dot{u}}$ = horizontal velocity and acceleration of water particles averaged over the submerged volume

v, $\dot{v}$ = velocity and acceleration of water particles in z-direction

$\bar{v}$, $\bar{\dot{v}}$ = vertical velocity and acceleration of water particles averaged over the submerged volume

V = submerged volume of a member

x,y,z = cartesian coordinates

$x,\dot{x},\ddot{x}$ = horizontal displacement, velocity and acceleration of the platform

δ = a member's equilibrium position from the origin in the coordinate system

ω = circular frequency of wave oscillations = $2\pi/T$

η = wave profile

ϕ = velocity potensial

$\mu_1 = \dfrac{\cosh k(h+z)}{\cosh kh}$

$\mu_2 = \dfrac{\sinh k(h+z)}{\sinh kh}$

$\mu_3 = \dfrac{\cosh k(h+z)}{\sinh kh}$

ρ = water density

$\phi(f)$ = response spectral density

$\phi_{1/3}$ = average of highest one-third of peak to trough values

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