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THE BEHAVIOUR OF A FIVE-COLUMN FLOATING DRILLING UNIT IN WAVES

(HET GEDRAG IN GOLVEN VAN EEN DRIJVEND BOOREILAND MET VIJF KOLOMMEN)

by

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VOORWOORD

Weinig is bekend over het gedrag van drijvende eilanden in zeegang. De gunstige vooruitzichten voor wat betreft de ontwikkeling van de werkzaamheden buitengaats, bleek bij het bedrijfsleven de belangstelling voor een onderzoek naar het gedrag van dergelijke objecten in golven opgewekt te hebben.

De resultaten van een dergelijk onderzoek zijn van groot belang voor het ontwerp en de exploitatie van drijvende eilanden. Het onderhavige rapport is een eerste stap in dit onderzoek, waarin nog vele problemen om een oplossing vragen.

Het beschouwde eiland is er een van het „Semi-submerged" type. Langs theoretische weg is voor dit 5-poots eiland het stelsel bewegingsvergelijkingen opgesteld, waarbij omwille van de vereenvoudiging bepaalde noodzakelijke verwaarlozingen zijn gepleegd.

Langs modelexperimentele weg zijn de coëfficiënten van de bewegingsvergelijkingen bepaald door excitatieproeven met het gefixeerde model. De golfopwekkende krachten zijn bepaald d.m.v. proeven met gefixeerd model in regelmatige golven.

Deze proeven werden uitgevoerd bij waterdiepten welke overeenkomen met 30, 40, 50 en 125 m in de werkelijkheid. De met behulp van de resultaten van deze proeven berekende responsiekarakteristieken, zijn vergeleken met de resultaten van proeven met het verankerde model in regelmatige en onregelmatige golven in een waterdiepte overeenkomend met 125 m. De onregelmatige golven zijn beschreven d.m.v. twee Noordzeespectra en een spectrum voor de kust van Nigeria, met dien verstande dat een langkammige zee is beschouwd. Voorts zijn methoden aangegeven voor de berekening van coëfficiënten en golfopwekkende krachten.

De resultaten tonen aan dat de berekeningen redelijk overeenstemmen met de uitkomsten van de modelproeven, hetgeen optimalisering van het ontwerp van het booreiland vanuit de theoretisch-analytisch kant met behulp van de bewegingsvergelijkingen zou rechtvaardigen.

Zeer interessant zou het zijn, om de correlatie tussen de bewegingen van het eiland op ware grootte, en die van het model te toetsen. Van groot belang is tevens de studie van de laag frequente verschijnselen, welke in het onderhavige rapport buiten beschouwing zijn gelaten.

De terbeschikkingstelling van de gegevens van het vijf kolommen booreiland door Bureau Marcon zij hier met dank vermeld.

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PREFACE

Very little is known about the behaviour of floating platforms in a seaway. The prospects for the development of offshore activities being favourable, the industry showed interest in an investigation into the behaviour of semi-submersibles in waves.

The results of such a study are of great importance for the design and operation of floating platforms. This report is a first step in this study which in many problems still have to be dealth with.

Subject of the investigation is a five-column floating drilling platform, of the semi-submerged type.

First, the mathematical description of the behaviour of the platform is given by means of the equations of motion, making use of certain necessary approximations. The coefficients in these equations have been determined by means of oscillation tests. Captive model test in regular waves have been carried out to obtain values for the wave exciting forces. The tests mentioned so far have been carried out in waterdepths corresponding to 30, 40, 50 and 125 meters.

The results obtained from these model tests make it possible to calculate the response functions of the platform. These calculated responses have been compared to the actual responses measured at the anchored model in regular and irregular waves in a waterdepth corresponding to 125 meters. The energy distributions of the irregular waves matched two different sea-states of the Northsea and one sea state off Nigeria respectively, however, a long crested sea has been considered.

Some methods are indicated to calculate coefficients and wave exciting forces of the equations of motion.

The results show a rather good agreement between calculated and measured values of motions and forces, and justify the use of the equations of motion in determining the optimum design of the platform.

It would be very interesting indeed to investigate the correlation between full scale and model test results.

Also of great importance is an investigation into low-frequency phenomena. The latter have been kept out of this study.

The kind cooperation of Bureau Marcon in providing the data of the five column drilling platform be gratefully mentioned here.

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CONTENTS

LIST OF SYMBOLS

A_{mm}	$(M_m + p_{mm})$
F_m	external force or moment F in the direction m
K	moment around longitudinal axis
M_m	mass or moment of inertia
M	moment around lateral axis
N	moment around vertical axis
T	period of oscillation
X	longitudinal force
Y	lateral force
Z	vertical force
c	spring constant of the anchoring system
d	water depth
m	wave number $= 2\pi/\lambda$
m_n	moment of spectral distribution $= \int_0^\infty \omega^n f_{hh(\omega)} \mathrm{d}\omega$
f_n	response function of a motion to waves
$\bar{f}_n$	ratio of motion amplitude to wave amplitude
f_{hh}	spectral density (energy spectrum) of the sea
f_{ss}	spectral density of the platform motions
g	acceleration due to gravity
g_n	response function of a force to waves
$\bar{g}_n$	ratio of amplitude of wave excited force to the amplitude of the wave height
h	elevation of the water surface
$\bar{h}$	wave height amplitude
i	$\sqrt{-1}$
h_{mn}	response operator or response function of a motion in direction n to a force in direction m
$\bar{h}_{mn}$	ratio of motion amplitude s_n to a force amplitude F_m
p_{mn}	added mass or moment of inertia of added mass
p	pressure
q_{mn}	damping coefficient
r	hydrostatic spring coefficient
s_n	motion s in the direction n
$\bar{s}$	amplitude of motion
t	time
w_{mn}	weighting function = time response function or impulsive response of the motion s_n to an impuls in direction m
x	surge
y	sway
z	heave
α_{mn}	phase difference between a motion s_n and a force F_m
β	wave direction
β_m	phase difference between a force F_m and the wave motion
ω	frequency of oscillation $= 2\pi/T$
ϕ	roll
ϑ	pitch
ψ	yaw
ε_n	phase difference between the wave motion and the platform motion in a direction n
ϱ	density of the water
δ	logarithmic decrement
λ	wave length
ν_{sj}	phase angle of the j^{th} component of regular motion
ω_m	frequency for which a wave exciting force becomes minimum
ω_n	natural frequency of oscillation

THE BEHAVIOUR OF A FIVE-COLUMN FLOATING DRILLING UNIT IN WAVES

by

Ir. J. P. HOOFT

Summary

A description is given of a detailed investigation into the behaviour of a floating drilling platform.
This investigation involves both theory and model testing. Some model tests were carried out in order to measure the hydrodynamic coefficients and wave exciting forces of the platform while other tests were performed to verify the calculations of the behaviour of the platform at her drilling location.
A good agreement between the calculations and the model test results was found.
Based on this finding a consideration is given in what way the calculations can be extended for the prediction of the behaviour under different conditions and of the forces acting on parts of the construction.

1 Introduction

In order to determine whether a drilling platform can fulfil its job at the location in mind one would like to predict the behaviour of the platform.

First of all it will be necessary to measure what the prevailing conditions such as wind, waves and current at the drilling location will be.

When this is known it can be tried to predict the behaviour of the platform by extrapolating from other sea conditions in which the platform has been in operation already. When the margin of safety obtained by this method is too small, model tests are carried out in a simulated sea condition corresponding to the actual condition.

For this it is necessary that the correlation between full scale and model test results has been investigated.

When, however, as was the case for the present investigation, the drilling platform is still in the design stage, a more extensive model test programme has to be carried out of which the purpose is twofold:

- First, extensive information is needed about the behaviour of the platform under several conditions, to enable extrapolation of the behaviour to all other conditions.
- Secondly, as much information as possible is needed to verify theoretical calculations of the characteristics of the platform to be able to optimize the behaviour of the platform by changing its dimensions. (This optimization may be restricted by other demands from a point of view of operation or strength etc.).

Tests have been carried out with a model of a five-column floating drilling platform, designed by Bureau Marcon [1]. The principal dimensions are given in fig. 1.

The information required as described above was obtained by carrying out the following test programme:

a. Captive model tests to determine the hydrodynamic characteristics of the prototype design of the platform such as added mass, damping and forces excited by waves.
b. Model tests with the anchored model to obtain the natural frequencies and to determine the response functions of the platform motion to some external force.
c. Model tests with the anchored model in irregular waves to determine the behaviour of the platform in some sea states.

In this report first an elucidation will be given of the theoretical considerations which led to this test programme. After this a description of the model test procedure will be given.

In the discussion of the model test results a comparison will be made between the results measured on

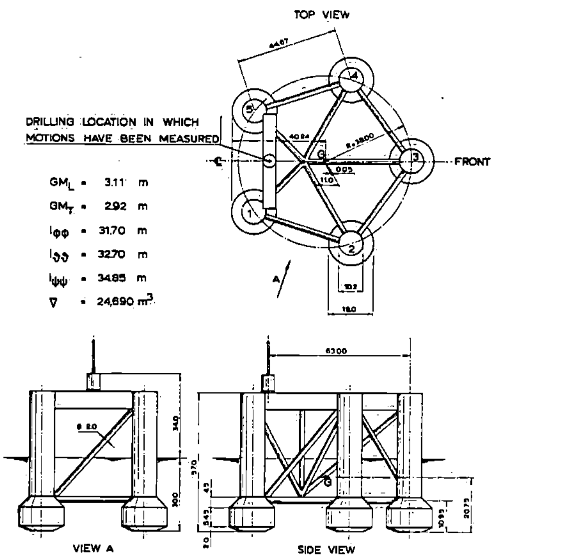


Fig. 1. Principal dimensions of the platform (Dimensions are in m for the full size).

model scale and the values that can be obtained theoretically.

In the present study only that part of the wave force will be discussed that oscillates with the same frequency as the waves.

This means that no analysis will be made of the drifting forces. The reason for this lies in the fact that the wave frequency motions of the platform have to be considered first while optimizing the behaviour of the platform.

Thereafter another study about the positioning by anchors or other means has to be made in which the low frequency forces on the platform are taken into account. This other study is still carried on. Two parts of it have been finished i.e. the drifting forces on a vertical circular cylinder in regular waves have been calculated by Flokstra [2] and the drifting forces on a body in irregular waves have been analysed by Hermans [3] and Verhagen [4].

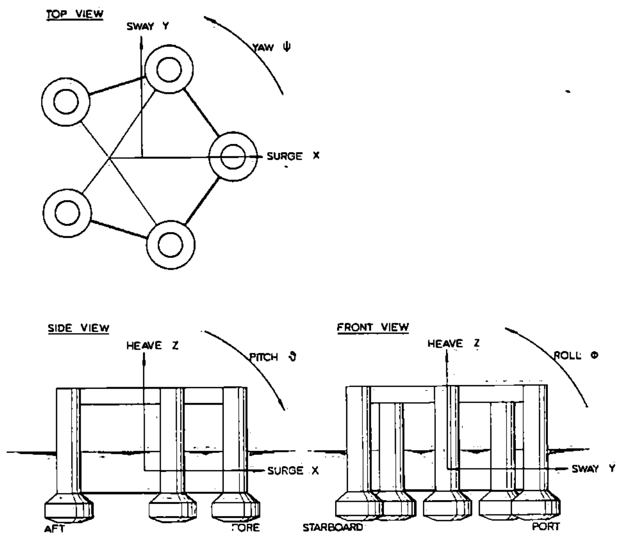


Fig. 2. Definition of coordinate system

2 Mathematical description of the behaviour of the platform

2.1 *Differential equations of motion*

In order to describe the motions of a floating drilling platform use is made of the differential equations of motion.

The basic form of the equations is deduced from Newton's law:

$$\bar{F} = M_m \frac{d^2\bar{s}}{dt^2} \tag{1}$$

in which:

$\bar{F}$ = resultant force or moment acting on the platform

M_m = mass or moment of inertia of the platform

$\bar{s}$ = displacement or rotation of the platform

$\frac{d\bar{s}}{dt}$ = velocity of the platform

$\frac{d^2\bar{s}}{dt^2}$ = acceleration of the platform

The motion $\bar{s}$ can be split up in six components as is indicated in figure 2.

The motions are defined by:

$s_1 - x -$ surge; $s_2 - y -$ sway; $s_3 - z -$ heave

$s_4 = \phi -$ roll; $s_5 - \vartheta -$ pitch; $s_6 = \psi -$ yaw

The forces are defined by:

X = longitudinal force
Y = lateral force
Z = vertical force
K = moment around longitudinal axis
M = moment around lateral axis
N = moment around vertical axis

First the forces acting on the platform due to its motions will be considered.

These forces F_{I} and F_{II} are introduced by a displacement as well as a velocity and an acceleration of the platform. It should be noted that the motion s_n in one direction not only introduces forces $F_{\text{I}} = F_n\,(s_n, \mathrm{d}s_n/\mathrm{d}t, \mathrm{d}^2s_n/\mathrm{d}t^2)$ in the same direction of the motion but also can introduce forces $F_{\text{II}} = F_m\,(s_n, \mathrm{d}s_n/\mathrm{d}t, \mathrm{d}s^2{}_n/\mathrm{d}t^2)$ in other directions. If only small motions of the platform are regarded the following linearized approximation is obtained:

$$F(s, \mathrm{d}s/\mathrm{d}t, \mathrm{d}^2s/\mathrm{d}t^2) = -p\frac{\mathrm{d}^2s}{\mathrm{d}t^2} - q\frac{\mathrm{d}s}{\mathrm{d}t} - rs \tag{2}$$

in which the following nomenclature is used:

p = added mass
q = damping coefficient
r = hydrostatic spring coefficient

Combining equation (1) and (2) one finds by describing the six degrees of freedom, six equations of motion:

$$
\begin{aligned}
a_{xx}x + a_{xy}y + a_{xz}z + a_{x\phi}\phi + a_{x\vartheta}\vartheta + a_{x\psi}\psi &= X\\
a_{yx}x + a_{yy}y + a_{yz}z + a_{y\phi}\phi + a_{y\vartheta}\vartheta + a_{y\psi}\psi &= Y\\
a_{zx}x + a_{zy}y + a_{zz}z + a_{z\phi}\phi + a_{z\vartheta}\vartheta + a_{z\psi}\psi &= Z\\
a_{\phi x}x + a_{\phi y}y + a_{\phi z}z + a_{\phi\phi}\phi + a_{\phi\vartheta}\vartheta + a_{\phi\psi}\psi &= K\\
a_{\vartheta x}x + a_{\vartheta y}y + a_{\vartheta z}z + a_{\vartheta\phi}\phi + a_{\vartheta\vartheta}\vartheta + a_{\vartheta\psi}\psi &= M\\
a_{\psi x}x + a_{\psi y}y + a_{\psi z}z + a_{\psi\phi}\phi + a_{\psi\vartheta}\vartheta + a_{\psi\psi}\psi &= N
\end{aligned} \tag{3}
$$

in which:

$a_{mn} = (\delta_{mn}M_m + p_{mn})\, \mathrm{d}/\mathrm{d}t^2 + q_{mn}\, \mathrm{d}/\mathrm{d}t + r_{mn}$
M_m = mass or moment of inertia of the platform
$\delta_{mn} = 1$ if $m = n$
$\delta_{mn} = 0$ if $m \neq n$

The forces X, Y and Z and moments K, M and N in equation (3) are caused by external influences such as the forces introduced by waves, wind, current, propulsion devices, anchor chains, rudders, damping systems etc.

The equations given in (3) are no real differential equations as the coefficients p_{mn} and q_{mn} depend on the frequency of oscillation of the external forces. In order to obtain real differential equations an extra term should be added in the left hand side of equations (3) as has been discussed by Ogilvie [5].

The coefficients of the equations (3) can be obtained experimentally. To simplify the measuring technique, an estimate has to be made first to determine what coefficients have to be taken into account. After the tests have been performed, it may be found that still some more of these coefficients could be neglected. For the platform in mind the assumptions were:

a. Due to surge no forces will be generated in lateral and vertical directions, nor will a moment be exerted around the longitudinal and the vertical axis and vice versa.
b. Due to sway and yaw no forces will be measured in the longitudinal and the vertical directions, nor will a moment be exerted around the lateral axis and vice versa.

The resulting equations of motions then become:

$$
\begin{aligned}
A_{xx}\ddot{x} + q_{xx}\dot{x} + c_{xx}x + p_{x\vartheta}\ddot{\vartheta} + q_{x\vartheta}\dot{\vartheta} + c_{x\vartheta}\vartheta &= X\\
A_{yy}\ddot{y} + q_{yy}\dot{y} + c_{yy}y + p_{y\phi}\ddot{\phi} + q_{y\phi}\dot{\phi} + c_{y\phi}\phi &= Y\\
A_{zz}\ddot{z} + q_{zz}\dot{z} + (r_{zz} + c_{zz})z + r_{z\vartheta}\vartheta &= Z\\
A_{\phi\phi}\ddot{\phi} + q_{\phi\phi}\dot{\phi} + (r_{\phi\phi} + c_{\phi\phi})\phi + p_{\phi y}\ddot{y} + q_{\phi y}\dot{y} + c_{\phi y}y &= K\\
A_{\vartheta\vartheta}\ddot{\vartheta} + q_{\vartheta\vartheta}\dot{\vartheta} + (r_{\vartheta\vartheta} + c_{\vartheta\vartheta})\vartheta + p_{\vartheta x}\ddot{x} + q_{\vartheta x}\dot{x} + c_{\vartheta x}x + r_{\vartheta z}z &= M\\
A_{\psi\psi}\ddot{\psi} + q_{\psi\psi}\dot{\psi} + c_{\psi\psi}\psi + p_{\psi y}\ddot{y} + q_{\psi y}\dot{y} &= N
\end{aligned} \tag{3a}
$$

in which:

A_{mm} = total (virtual) mass or moment of inertia = $M_m + p_m$
p_{mn} = added mass or added moment of inertia
q_{mn} = damping coefficient
r_{mn} = spring constant due to buoyancy
c_{mn} = spring constant due to the anchoring system
m = indicates the direction of the force
n = indicates the direction of the motion

2.2 *Response functions of the motions to external forces*

As the coefficients p_{mn} and q_{mn} in the six equations (3) depend on the frequency of the external forces it is not yet possible to determine the motions of the platform for any arbitrary external force.

From the equations (3) it is only possible to calculate for each frequency the response of the platform to a harmonically oscillating force. However, this response only exists when the motions of the platform are stable.

The harmonically oscillating force in one direction is given by:

$$F_{m(\omega)} = F_m \sin \omega t$$

If the motion of the platform is stable it finally will achieve the following value:

$$s_n = \bar{s}_{n(\omega)} \sin(\omega t + \alpha_{mn(\omega)})$$

The response h_{mn} of the motion in the n-direction as a result of the force in the m-direction is described by the response operator $\bar{h}_{mn}$ and the phase difference α_{mn}:

$$h_{mn} = \bar{h}_{mn(\omega)} e^{i\alpha_{mn(\omega)}} \tag{4}$$

in which:

$$\bar{h}_{mn(\omega)} = \frac{\bar{s}_{n(\omega)}}{\bar{F}_m}$$

In Solodovnikov [6] (see also [7]) a description is given in which way the response of the motion can be deduced from equation (3):

$$h_{mn} = \frac{D_{mn}}{D} \tag{5}$$

in which:

$$D_{mn} = \begin{vmatrix} b_{11} \cdots b_{1(n-1)} b_{1(n+1)} \cdots b_{16} \\ \cdots\cdots\cdots\cdots\cdots \\ b_{(m-1)1} \cdots\cdots\cdots\cdots \\ b_{(m+1)1} \cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots \\ b_{61} \cdots\cdots\cdots\cdots b_{66} \end{vmatrix}$$

and

$$D = \begin{vmatrix} b_{11} \cdots\cdots\cdots\cdots b_{16} \\ \cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots \\ b_{61} \cdots\cdots\cdots\cdots b_{66} \end{vmatrix}$$

with:

$$b = (\delta_{mn} M_m + p_{mn})(i\omega)^2 + q_{mn}(i\omega) + (r_{mn} + c_{mn})$$

The determinant D_{mn} equals the determinant D except for the row m and the column n which have been cancelled.

Once the motions of the platform are determined as a response of a harmonically oscillating force it will be possible to determine the motion $s_n(t)$ of the platform for any external force $F_{m(t)}$ which is given as an arbitrary function of time:

$$s_{n(t)} = \frac{1}{\pi} \int_{-\infty}^{+\infty} R_{(\omega)} \cos \omega t \, d\omega \qquad \text{for } t > 0 \qquad (6)$$

in which:

$$R_{(\omega)} = P_{1(\omega)} \cdot P_{2(\omega)} - Q_{1(\omega)} \cdot Q_{2(\omega)}$$

$$P_{1(\omega)} = \bar{h}_{mn(\omega)} \cos \alpha_{mn(\omega)}$$

$$Q_{1(\omega)} = \bar{h}_{mn(\omega)} \sin \alpha_{mn(\omega)}$$

$$P_{2(\omega)} = \int_{-\infty}^{+\infty} F_{m(t)} \cos \omega t \, dt$$

$$Q_{2(\omega)} = \int_{-\infty}^{+\infty} F_{m(t)} \sin \omega t \, dt$$

while $F_{m(t)}$ as a function of time has to be absolutely integrable:

$$\int_{-\infty}^{+\infty} |F_{(t)}| \, dt < \infty$$

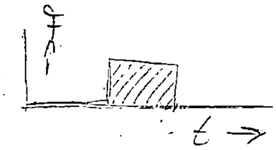
A more simple way to determine the motions of the platform as a function of time for any external force which is known as a function of time, is found by determining the weighting function (impulsive response) of the motions.

The weighting function gives the motion as a result of a unit impulse according to a delta function which is given by:

$$F_{m(t-t_0)} = 0 \quad \text{for} \quad t - t_0 < 0 \quad \text{and} \quad t - t_0 > \Delt$$

$$F_{m(t-t_0)} = \frac{1}{\Delta t} \quad \text{for} \quad 0 < t - t_0 < \Delta t$$

in such a way that:



$$\int_{-\infty}^{+\infty} F_{m(t-t_0)} \, dt = 1$$

The motion of the platform resulting from this impulse can be found from:

$$w_{mn(t)} = \frac{2}{\pi} \int_0^{+\infty} \bar{h}_{mn(\omega)} \cos \alpha_{mn(\omega)} \cos \omega t \, d\omega$$

in which:

w_{mn} = weighting function or impulsive response of the motion = time response function, which can be determined by measuring the ship motion after an impulse on the ship

Once the weighting function has been determined the motion of the platform as a result of an external force easily can be found from:

$$s_{n(t)} = \int_0^{\infty} F_{m(t-\tau)} \, w_{mn(\tau)} \, d\tau \qquad (7)$$

2.3 *Wave exciting forces*

The wave exciting forces can be determined when the platform is rigidly restrained in a wave train. First of all the exciting forces on the platform in regular waves are measured.

One then can determine the force response to a wave. This response function g_m of the force is defined by the response operator $\bar{g}_m$ and the phase difference β_m, in which:

$$g_m = \bar{g}_m e^{i\beta_m}; \quad \bar{g}_m = \frac{\bar{F}_m}{\bar{h}} \qquad (8)$$

while β_m follows from the phase difference between the motion of the waves:

$$h = \bar{h} \sin \omega t$$

and the oscillating forces:

$$F_m = \bar{F}_m \sin(\omega t + \beta_m)$$

Once now for each frequency the wave exciting force is known as a linear function of the wave height, also the forces in an irregular sea state are known, supposing that the superposition principle holds.

For this, similar formulas are used as given in section 2.2.

When in an irregular long-crested sea state the wave height $h_{(t)}$ is given as a function of time, the wave force then follows from:

$$F_{m(t)} = \frac{1}{\pi} \int_{-\infty}^{+\infty} \bar{g}_{m(\omega)} \cos \omega t \, d\omega \qquad t > 0 \tag{9}$$

in which:

$$g_{(\omega)} = \pi_{1(\omega)}\pi_{2(\omega)} - F_{1(\omega)}F_{2(\omega)}$$

$$\pi_{1(\omega)} = \bar{g}_{m(\omega)} \cos \beta_{m(\omega)}$$

$$F_{1(\omega)} = \bar{g}_{m(\omega)} \sin \beta_{m(\omega)}$$

$$\pi_{2(\omega)} = \int_{-\infty}^{+\infty} h_{(t)} \cos \omega t \, dt$$

$$F_{2(\omega)} = -\int_{-\infty}^{+\infty} h_{(t)} \sin \omega t \, dt$$

It will be clear that in this case no use can be made of a weighting function since it will be physically impossible to generate an impulsive surface elevation corresponding to the delta function described earlier.

2.4 *Response functions of the platform to waves*

2.4.1 Motions in regular waves

When for each height and frequency of regular waves the exciting forces on the platform have been determined one can substitute the response function of the force to waves defined by equation (8) into equation (4).

From this the response function f_n of the motion s_n of the platform to regular waves $h_{(\omega)}$ can be calculated as follows:

$$f_{n(\omega)} = h_{mn(\omega)} e^{i\alpha_{mn}} g_{m(\omega)} e^{i\beta_m} =$$

$$= \sum_{m=1}^{6} \left(\frac{\bar{s}_n}{\bar{F}_m}\right)_{(\omega)} e^{i\alpha_{mn}} \frac{\bar{F}_{m(\omega)} e^{i\beta_m}}{\bar{h}} = \left(\frac{\bar{s}_n}{\bar{h}}\right)_{(\omega)} e^{i\varepsilon_n} \tag{10}$$

2.4.2 Motions in irregular waves

When in a given sea state the wave exciting force $F_{m(t)}$ has been determined by equation (9) as a function of time then also the motions of the platform are known as a function of time by substituting the exciting force given by equation (9) into either equation (6) or (7).

It now may be concluded that if all the hydrodynamic properties of the platform are known it will be possible to calculate the motion of the platform in an irregular long-crested sea.

This result is of importance if one wants to know if the behaviour of the platform will be good enough in some given sea state which has been measured at the drilling location.

Generally the most important criterion of the behaviour of the platform is only the demand that the motions may not exceed a predetermined value.

This means that one is not so much interested in the behaviour of the platform as a function of time but only wants to know the maximum value of the motion that can occur in the given sea condition.

In this case another method mostly is used.

One then only needs to know the response function of the motion of the platform in regular waves as given in equation (10).

From the measurements of the sea state one determines the energy distribution (spectrum) of the sea.

By means of equation (7) one then can deduce that:

$$f_{ss(\omega_j)} = f_{hh(\omega_j)} \left[\frac{\bar{s}_{n(\omega_j)}}{\bar{h}}\right]^2 \tag{11}$$

in which:

$f_{hh(\omega_j)}$ = spectral density (energy spectrum) of the sea $= \frac{\bar{h}_j^2}{2} \frac{1}{d\omega}$

$f_{ss(\omega_j)}$ = spectral density of the motions $= \frac{\bar{s}_j^2}{2} \frac{1}{d\omega}$

while h_j and s_j are the amplitudes of the j^{th} component of an infinite number of components of regular motions:

$$h_{(t)} = \sum_{j=0}^{\infty} \bar{h}_j \cos(\omega_j t + v_{hj})$$

$$s_{(t)} = \sum_{j=0}^{\infty} \bar{s}_j \cos(\omega_j t + v_{sj})$$

From equation (11) it follows, that if the spectrum of the sea and the response of the motion in regular waves is known also the energy distribution of the motions of the platform are known.

The total energy of some motion amounts to:

$$m_0 = \int_0^{\infty} f_{ss(\omega)} d\omega \tag{12a}$$

From this the significant value $\bar{s}_{\frac{1}{3}}$ and the mean period of some motion can be determined:

$2\bar{s}_{\frac{1}{3}}$ = average of $\frac{1}{3}$ highest peak to through values $= 4\sqrt{m_0}$

$\bar{T}$ = mean period of oscillation $= 2\pi \frac{m_0}{m_1}$

$$\text{with } m_1 = \int_0^{\infty} \omega f_{ss(\omega)} d\omega \tag{12b}$$

Once the standard deviation σ (equal to $\sqrt{m_0}$) or the significant value of the motion is known one can calculate by means of a statistical analysis the chance that the motion of the platform will exceed some maximum value. For linear motions use can be made of the theory of Cartwright [8].

The results of this theory are given in Table I.

Table I. Chance that the maximum value of a motion will exceed a predetermined limit of $2a\sqrt{m_0} = 2a\sigma$

number of oscillations N	chance p 63% (most probable)	50%	10%	5%	1%
100	a = 1.54	1.58	1.85	1.95	2.14
200	1.64	1.68	1.94	2.04	2.22
500	1.77	1.82	2.06	2.14	2.32
1000	1.87	1.92	2.15	2.23	2.40
5000	2.07	2.10	2.32	2.40	2.56
10000	2.15	2.18	2.40	2.47	2.63

N = Number of oscillations = period of a sustained condition divided by the mean period of oscillation.

p = Chance that the maximum motion exceeds $2a\sigma$; this means that $(100-p)$% is the percentage of safety that the maximum motion will not exceed this value $2a\sigma$; in which $\sigma = \sqrt{m_0}$

3 Description of the model tests

3.1 *General*

The tests were carried out in the Wave and Current Basin and the Seakeeping Basin with Model no. 3404, made to a scale of 1 : 50.

The model tests were based on Froude's law of similitude. Consequently for the length scale of 50, the time and velocity scale become $\sqrt{50}$ and the force and mass scale 50^3. All results apply to salt water with a density of 1.025 ton/m^3.

3.2. *Captive model tests*

Captive tests at different waterdepths were carried out in order to obtain the hydrostatic and hydrodynamic coefficients, and the wave exciting forces of the linearized equations, which for the present case could be reduced to the equations (see equations 3a):

$$
\begin{aligned}
&(M + p_{xx})\ddot{x} + q_{xx}\dot{x} + p_{x\vartheta}\ddot{\vartheta} + q_{x\vartheta}\dot{\vartheta} &&= X\\
&(M + p_{yy})\ddot{y} + q_{yy}\dot{y} + p_{y\phi}\ddot{\phi} + q_{y\phi}\dot{\phi} &&= Y\\
&(M + p_{zz})\ddot{z} + q_{zz}\dot{z} + r_{zz}z + r_{z\vartheta}\vartheta &&= Z\\
&(I_{\phi\phi} + p_{\phi\phi})\ddot{\phi} + q_{\phi\phi}\dot{\phi} + r_{\phi\phi}\phi + p_{\phi y}\ddot{y} + q_{\phi y}\dot{y} &&= K\\
&(I_{\vartheta\vartheta} + p_{\vartheta\vartheta})\ddot{\vartheta} + q_{\vartheta\vartheta}\dot{\vartheta} + r_{\vartheta\vartheta}\vartheta + p_{\vartheta x}\ddot{x} + q_{\vartheta x}\dot{x} + r_{\vartheta z}z &&= M\\
&(I_{\psi\psi} + p_{\psi\psi})\ddot{\psi} + q_{\psi\psi}\dot{\psi} + r_{\psi\psi}\psi + p_{\psi y}\ddot{y} + q_{\psi z}\dot{y} &&= N
\end{aligned}
\tag{13}
$$

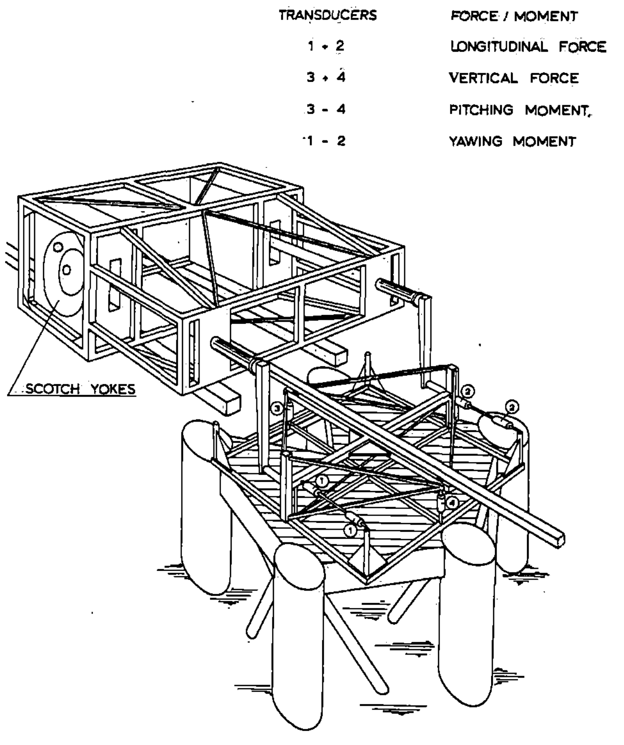


Fig. 3. Test set-up for oscillation tests

The equations of motion as given above are written in such a form that the coefficients can be found by oscillating the model harmonically in each direction separately.

No anchor chains were attached to the model during these tests. For the oscillation tests a frame was used as indicated in figure 3.

The hydrostatic buoyance coefficients r_{mn} were found by measuring the stationary force or moment F_m caused by a constant displacement s_n.

The results are stated in Table II.

Table II. Buoyancy coefficients

coefficient	unit	calculated	measured
heave r_{zz}	ton/m	464	449
$r_{\vartheta z}$	ton	48	163
roll $r_{\phi\phi}$	ton.m/rad	74820	75600
pitch $r_{\vartheta\vartheta}$	ton.m/rad	75830	74700
$r_{z\vartheta}$	ton/rad	48	163

For the determination of the hydrodynamic coefficients (added mass p_{mn} and the damping q_{mn}) the platform is forced to oscillate harmonically during which the forces and moments of all directions were measured.

Thus the motion will be:

$$s_n = \bar{s}_n \sin \omega t$$

in which:

$\bar{s}_n$ = amplitude of the motion
$\omega = 2\pi/T$ = frequency of the motion
T = period of the motion

The force or moment measured during the oscillations in a linearized case will amount to:

$$F_{mn} = \bar{F}_{mn} \sin(\omega t - \alpha_{mn})$$

in which:

F_{mn} = force or moment in the m-direction due to a motion in the n-direction
$\bar{F}_{mn}$ = amplitude of the force
α_{mn} = phase difference between the force and the motion; the difference in time between the force being maximum and the motion being maximum amounts to $\alpha T/2\pi$ seconds.

When the formula for F_{mn} is rewritten as:

$$F_{mn} = (\bar{F}_{mn} \cos \alpha_{mn}) \sin \omega t - (\bar{F}_{mn} \sin \alpha_{mn}) \cos \omega t$$

it follows that the components of the force which are in and out of phase with the model motion are respectively:

$\bar{F}_{mn} \cos \alpha_{mn}$ in phase

$\bar{F}_{mn} \sin \alpha_{mn}$ out of phase

The amplitude and period of the model motion being known the amplitude of the above force components can be found by means of a Fourier analysis:

$$\bar{F}_{mn} \cos \alpha_{mn} = \frac{1}{k\pi} \int_0^{2k\pi} F_{(t)} \sin \omega t \, d\omega t$$

$$\bar{F}_{mn} \sin \alpha_{mn} = \frac{1}{k\pi} \int_0^{2k\pi} F_{(t)} \cos \omega t \, d\omega t$$

By substituting the motion s_n and the force F_{mn} into equation (13) one finds:

$$[-(\delta_{mn} M_m + p_{mn})\,\omega^2 + r_{mn}]\,\bar{s}_n \sin \omega t + q_{mn}\bar{s}_n \cos \omega t =$$
$$= (\bar{F}_{mn} \cos \alpha_{mn}) \sin \omega t - (\bar{F}_{mn} \sin \alpha_{mn}) \cos \omega t$$

At the time $t_1 = \pi/2\omega = T/4$ one finds:

$$[-(\delta_{mn} M_m + p_{mn})\,\omega^2 + r_{mn}] = \frac{\bar{F}_{mn} \cos \alpha_{mn}}{\bar{s}_n}$$

From this one can also now determine the added mass p_{mn}, since the buoyancy coefficient r_{mn} is already known.

$$p_{mn} = \frac{r_{mn} - \dfrac{\bar{F}_{mn} \cos \alpha_{mn}}{\bar{s}_n}}{\omega^2} - \delta_{mn} M_m$$

At the time $t_2 = 0$ one finds:

$$q_{mn} = -\frac{\bar{F}_{mn} \sin \alpha_{mn}}{\omega \bar{s}_n}$$

by which also the damping coefficient q_{mn} is known.

In Figure 11a through 11e of the appendix all coefficients of equation (13) resulting from the experiments are given.

For the measurements of the wave exciting forces the model was held rigidly to a measuring bridge as shown in figure 4a.

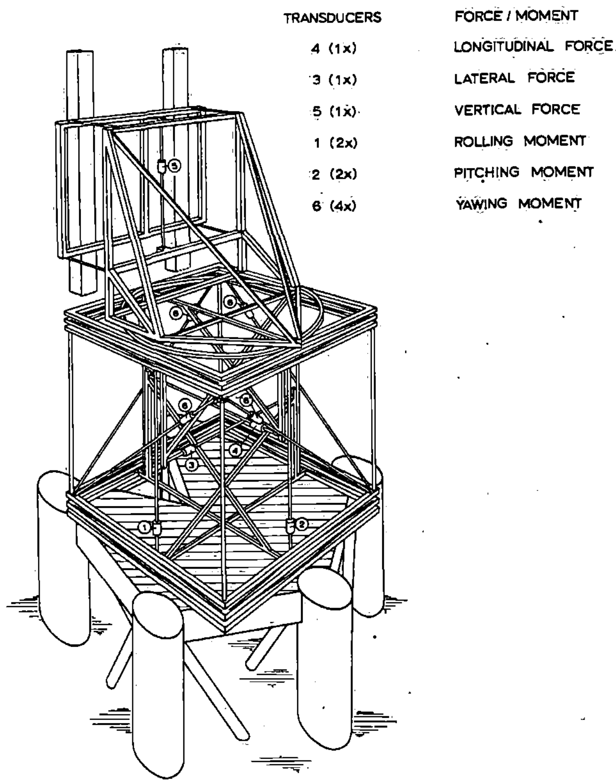


Fig. 4a. Test set-up for measurements of wave exciting force

During these tests the three forces and three moments in equation (13) acting on the model were recorded continuously, together with the wave elevation.

From the recordings of the measurements as indicated in figure 4b the amplitude F_m has been determined as a function of the wave amplitude.

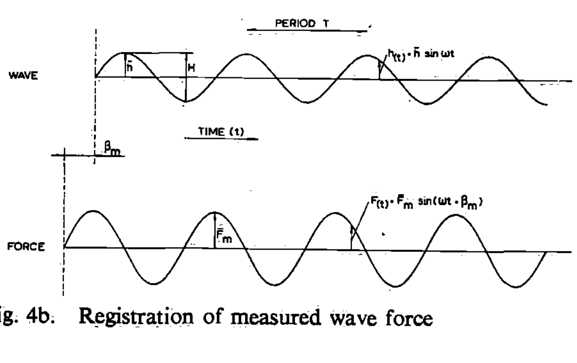


Fig. 4b. Registration of measured wave force

The ratios F_m/h as determined from the measurements have been plotted in figure 12a, 12b and 12c of the appendix on a base of the wave frequency.

Since the phase difference of the force relative to the wave depends upon the location at which the wave is measured, all phase angles have been related to the vertical force (see figure 12d and 12e).

3.3 *Tests with the anchored platform*

The anchored platform was tested in a water depth corresponding to 125 m.

The anchoring system was simulated in such a way that the anchoring characteristics corresponded to those of the actual anchoring configuration as indicated in figure 5a and with the following particulars:

a. The length of each of the 10 anchor chains amounts to 436 m.
b. The weight of the anchor chains amounts to 72 kgf per meter.
c. The pretension of the anchor chains corresponds to 22.4 tons.
d. The elasticity of the anchor chains corresponds to 30,000 ton/m/m.

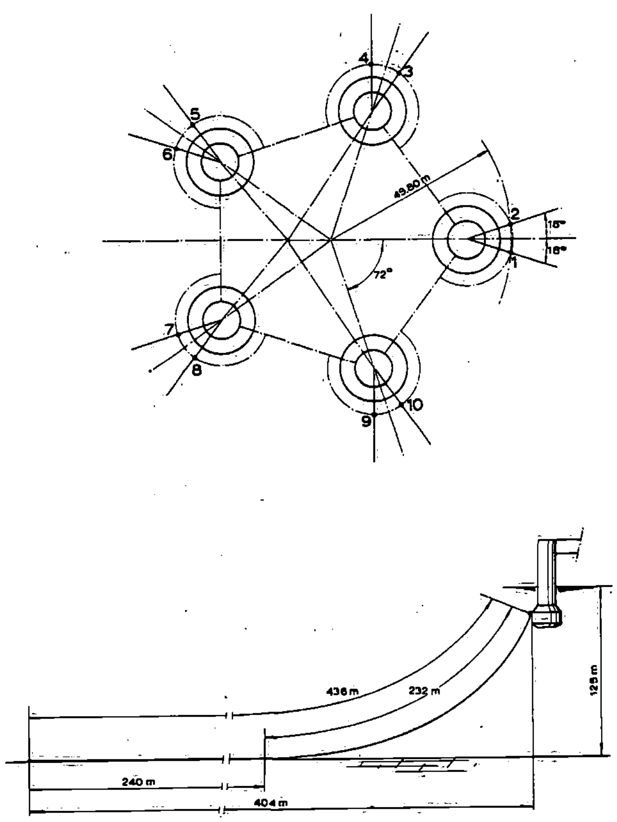


Fig. 5a. Anchoring system of the platform

The spring constants of the anchoring system can be calculated by using the equations for a catenary as given in figure 5b.

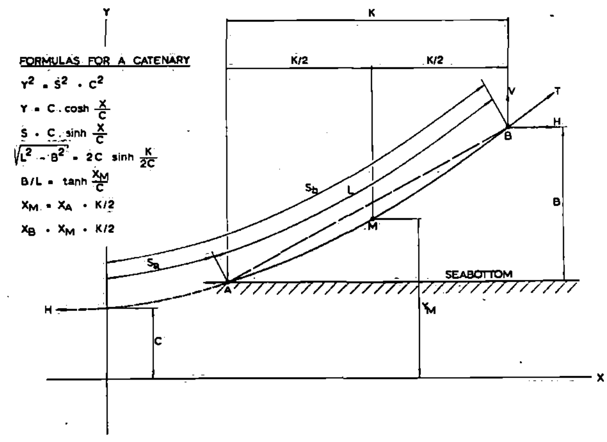


Fig. 5b. Determination of forces in anchor chains

As an example the spring coefficients for the coupled equations of surge and pitch have been calculated for the anchoring system that has been used during the tests in a water depth of 125 m (see figure 13 of the appendix):

$$c_{xx} = 6{,}000 \text{ kgf/m}$$

$$c_{\vartheta x} = 36{,}000 \text{ kgfm/m}$$

$$c_{\vartheta\vartheta} = 8{,}170{,}000 \text{ kgfm/rad}$$

$$c_{x\vartheta} = 58{,}140 \text{ kgf/rad}$$

First, extinction tests were carried out in such a way that the model was released after some disturbance from its equilibrium position (see figure 6).

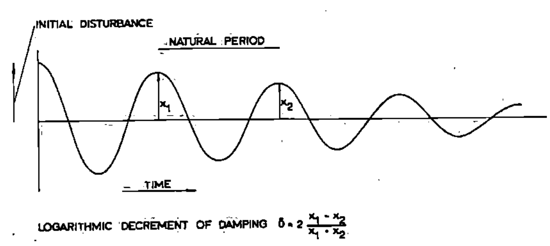


Fig. 6. Extinction test

In Table III the natural periods obtained from these tests are given.

Table III. Natural periods of anchored platform; measured from extinction tests at a water depth of 125 m

Surge	140 sec
Sway	125 sec
Heave	18.1 sec
Roll	44.5 sec
Pitch	45 sec
Yaw	145 sec

In Table IV the results of extinction tests with the free floating platform are given in comparison with the values calculated with the aid of the results of the captive model tests.

The calculated natural period amounts to:

$$T_n = 2\pi \sqrt{\frac{A_{nn}}{r_{nn} + c_{nn}}}$$

The calculated logarithmic decrement follows from:

$$\delta = \frac{q_{nn} T_n}{2A_{nn}} = \pi v$$

Table IV. Natural periods of free floating platform at a water depth of 50 m

motion	measured from extinction tests	calculated from measured coefficients
heave	18.0 sec	18.1 sec
roll	43.2 sec	44.5 sec
pitch	44.8 sec	45.0 sec

Logarithmic decrement of free floating platform at a water depth of 50 m

motion	measured from extinction tests	calculated from measured coefficients
heave	0,154	0,232
roll	0.113	0.105
pitch	0.143	0.174

3.4 *Tests in waves*

After this, tests in waves were carried out.

From the results of the captive model tests all response functions in regular waves could already be determined (see 2.4.1).

Some of the calculated response functions have been compared with the response functions determined from tests in regular long-crested waves, see figure 14, in which also the results are given of three tests performed in irregular waves, of which the energy distributions are given in figure 15.

The distributions of the anchor line forces are plotted in figure 16.

4 Analysis of the results

4.1 *Hydrodynamic coefficients*

It is quite difficult to calculate the added mass (virtual mass minus the mass of the object) for an arbitrary hull form.

Generally speaking, the added mass is mainly determined by the area perpendicular to the direction of oscillation (projected area).

Besides, the added mass is also influenced by the free water surface and by bottom effects.

In an infinite space the added mass is independent of the frequency of oscillation.

However, due to boundary effects the added mass will depend on the frequency of oscillation.

A review of the calculations of added mass on all kinds of objects is given by Kennard [9].

For some objects also the influence of bottom effects is given in this paper.

For a sphere and a horizontal cylinder the influence of the free water surface on the added mass has been analysed by Yamamoto [10]; see figure 7a and 7b.

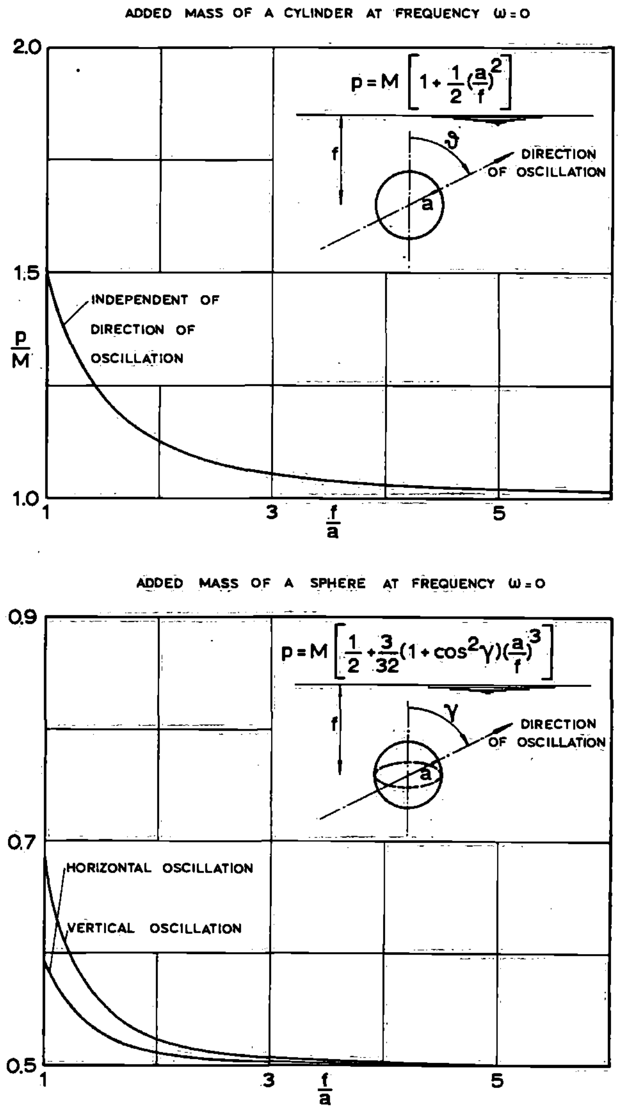


Fig. 7a-7b. Added mass calculated by Yamamoto

While using the above-mentioned literature the added mass of the platform can be estimated.

Only one addition to the information given by literature has to be made; this is the assumption that the added mass of a cylinder which oscillates in an arbitrary direction relative to its longitudinal axis can be deduced as indicated by figure 8.

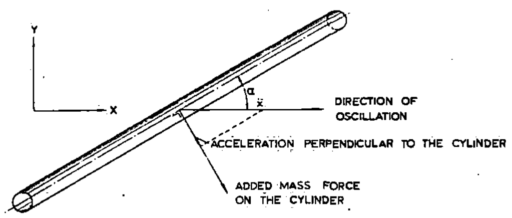


Fig. 8. Added mass of cylinder moving in an arbitrary direction relative to the longitudinal axis

The added mass force due to an acceleration in the x-direction amounts to $p \cdot \ddot{x} \sin \alpha$ while its direction is perpendicular to the longitudinal axis of the cylinder. The added mass in the direction x therefore amounts to:

$$p_{xx} = p \sin^2\alpha$$

in which:

p = added mass of a cylinder when moved in a direction perpendicular to the cylinder axis;

while:

$$p_{yx} = -p \sin \alpha \cos \alpha$$

From figure 11 it follows that the added masses calculated in this way are in good agreement with the values measured. This is an important result since it will now be possible to calculate also the added mass of a hull with slightly different dimensions relative to the prototype.

When oscillated in an infinite space the damping is only effectuated by friction.

The damping of a floating object, however, is also influenced by potential effects.

In this case the damping will be a function of the energy that is dissipated by outward travelling waves. Therefore it is clear, that this damping will be related to the force excited by waves travelling along the object as is shown by Newman [11] and [12].

From [13] the relation between damping and wave exciting force on shallow water can be taken:

$$q_{mn} = \frac{\omega^3}{2\pi \varrho g^3 \varkappa} \int_0^\pi \left[\frac{F_{m(\nu)}}{h}\right]^2 d\beta \tag{15}$$

with:

q_{mn} = damping coefficients in the m-direction

$F_{m(\nu)}$ = wave exciting force in the m-direction due to waves coming in a direction of ν degrees with the longitudinal axis of the platform.

$$\varkappa = \frac{md \tanh md}{\cosh^2 md}\left(1 + \frac{\sinh^2 md}{2md}\right)$$

4.2 *Wave exciting forces*

According to [13] it may be concluded that the oscillatory wave force on a small body in an incompressible, irrotational and inviscid fluid can be calculated by adding the following parts:

Part 1: The undisturbed pressure force F_1, which is the force that arises from the pressure on the hull in a wave that is not disturbed by the hull.

Part 2: The added mass force F_{21}, which is the force that arises from the acceleration of the added mass of the hull in a wave that is not disturbed by the hull.

Part 3: The damping force F_{22}, which is the force that arises from the damping due to the hull, of the velocity of the water particles in a wave that is not disturbed by the hull.

The added mass and damping mentioned under part 2 and 3 are the same as those determined from the oscillation tests. It should be noted that for the calculation of the added mass force and the damping force the acceleration and velocity of the water particles on the undisturbed wave have to be used. The forces in part 1 and 2 are out of phase with part 3 of the force.

The approximation holds true for bodies of which the dimensions are 5 times smaller than the wave length.

In that case the maximum difference between the appoximation and the exact theory is 5%.

When the forces on a cylinder have to be calculated this theory can still be maintained by cutting up the cylinder in strips.

An extensive description of the determination of the wave exciting forces has been given in [14].

The results of the calculations according to [14] are given in figure 12a through 12e of the appendix together with the model test results.

The wave exciting forces determined by this calculation method were calculated by adding the wave exciting forces on parts of the platform which were substituted by simple hull forms.

In the following some examples are given to illustrate the method by which the forces on some elements of the whole structure can be determined.

When the wave profile is given by:

$$h_{(t)} = \bar{h} \sin(\omega t - m\xi) \tag{16}$$

it can be found that the pressure variation at some distance below the still water surface follows from:

$$p - p_1 = \mu_1 \varrho \, gh \sin(\omega t - m\xi) \tag{17}$$

The relation between the wave number m and the wave frequency ω follows from:

$$\omega^2 = gm \tanh mh \tag{18}$$

The velocity of the wave particles follows from:

$$\dot{\xi} = \mu_3 \omega \bar{h} \sin(\omega t - m\xi) \tag{19}$$
$$\dot{\zeta} = \mu_2 \omega \bar{h} \cos(\omega t - m\xi)$$

in which:

ξ = longitudinal position of the water particles in the direction of propagation of the waves;
ζ = vertical position of the water particles;

while the acceleration of the water particles amounts to:

$$\ddot{\xi} = \frac{\partial \dot{\xi}}{\partial t} = \mu_3 \omega^2 \bar{h} \cos(\omega t - m\xi)$$
$$\ddot{\zeta} = \frac{\partial \dot{\zeta}}{\partial t} = -\mu_2 \omega^2 \bar{h} \sin(\omega t - m\xi) \tag{20}$$

The μ coefficients in equation (17), (19) and (20) are given by:

$$\mu_1 = \frac{\cosh m(d+\zeta)}{\cosh md}$$
$$\mu_2 = \frac{\sinh m(d+\zeta)}{\sinh md}$$
$$\mu_3 = \frac{\cosh m(d+\zeta)}{\sinh md}\left(= \frac{\mu_5}{\omega}\right) \tag{21}$$
$$\mu_4 = \frac{\sinh m(d+\zeta)}{\cosh md}$$

The μ coefficients are plotted in figure 17 through 20.

Once the motions of the water-particles are known, the wave exciting forces can be determined.

Example 1

Horizontal cylinder of which the length l is large relative to the diameter D (see figure 9).

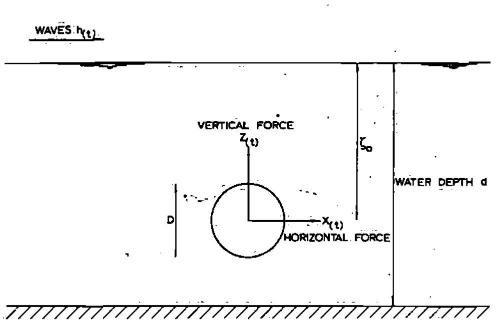


Fig. 9. Wave exciting forces on a horizontal cylinder.

The added mass of the cylinder equals the mass of the cylinder when no effects of the bottom or the water surface are introduced:

$$p_{zz} = p_{xx} = M = \varrho \frac{\pi}{4} D^2 l \tag{22}$$
$$p_{zx} = p_{xz} = 0$$

The wave exciting forces according to the review in the beginning of this section, amount to:

$$\bar{x} = \sqrt{(\bar{x}_1 + \bar{x}_{21})^2 + x_{22}^2} \tag{23}$$
$$\bar{z} = \sqrt{(\bar{z}_1 + \bar{z}_{21})^2 + z_{22}^2}$$

in which:

$$\left.\begin{aligned} \bar{x}_1 &= \bar{x}_{21} = \frac{\varrho\pi}{4} D^2 l \mu_3 \omega^2 \bar{h} \\ \bar{x}_{22} &= q_{xx} \mu_3 \omega \bar{h} \end{aligned}\right] \mu_3 \text{ for } \zeta = \zeta_0$$
$$\left.\begin{aligned} \bar{z}_1 &= \bar{z}_{21} = \frac{\varrho\pi}{4} D^2 l \mu_2 \omega^2 \bar{h} \\ \bar{z}_{22} &= q_{zz} \mu_2 \omega \bar{h} \end{aligned}\right] \mu_2 \text{ for } \zeta = \zeta_0 \tag{24}$$

Example 2

Vertical cylinder with diameter D (see Figure 10). The added masses follow from:

$$p_{xx} = M = \varrho \frac{\pi}{4} D^2 l$$
$$p_{zz} = \frac{\pi}{6} D^3 \tag{25}$$
$$p_{zx} = p_{xz} = 0$$

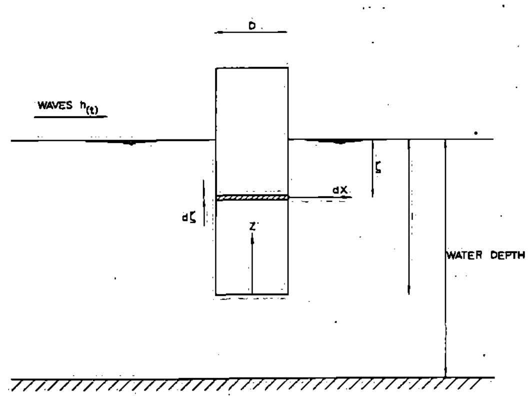


Fig. 10. Wave exciting forces on a vertical cylinder.

The wave exciting forces according to the review in the beginning of this section, amount to:

$$\bar{x} = \sqrt{(\bar{x}_1 + \bar{x}_{21})^2 + x_{22}^2} \tag{26}$$
$$\bar{z} = \sqrt{(\bar{z}_1 + \bar{z}_{21})^2 + z_{22}^2}$$

in which:

$$\bar{x}_1 = \bar{x}_{21} = \frac{\varrho\pi D^2}{4}\omega^2\bar{h}\int_{-l}^{0}\mu_3 d\zeta =$$

$$= \frac{\varrho\pi D^2}{4}\frac{\omega^2 h}{m}\left(1 - \frac{\sinh m(d-l)}{\sinh md}\right)$$

$$\bar{x}_{22} = \frac{dq_{xx}}{d\zeta}\omega\bar{h}\int_{-l}^{0}\mu_3 d\zeta \qquad (27)$$

$$\bar{z}_1 = \frac{\pi}{4}D^2\varrho g\bar{h}\frac{\cosh m(d-l)}{\cosh md}$$

$$\bar{z}_{21} = \frac{\varrho}{6}D^3\omega^2\bar{h}\frac{\sinh m(d-l)}{\sinh md}$$

$$\bar{z}_{22} = q_{zz}\omega\bar{h}\frac{\sinh m(d-l)}{\sinh md}$$

Once the wave exciting force on one vertical cylinder is known the wave exciting force can be determined on a platform consisting of 5 columns positioned to each other in the same way as in the case of the platform described in this paper.

Due to the fact that the wave action on each column has a phase difference in time, the total force will be less than 5 times the force on one column.

The factor being the ratio between the force on a platform of 5 columns and the force on 5 fictive columns in the centre of gravity of the platform is given in Figure 21.

Far from being complete the examples given above will elucidate the calculations of the wave exciting forces on the whole structure.

4.3 *Recapitulation of the results obtained*

Up to now a description has been given of the factors that determine the behaviour of the drilling platform.

With the use of the equations given it will be possible to determine whether the drilling platform can be improved.

If so, the equations can be used to determine in what way improvements can be obtained.

The determination of the optimum design of the platform is not within the scope of this project.

However, some examples will be dealt with to get a rough idea to what results these studies will lead.

The heave response for those frequencies in which the waves have the largest energy, will change at decreasing water depths.

This is caused among other things by the change of the frequency ω_m at which the vertical wave exciting force is minimum.

The heave response function can be changed in several ways, e.g.:

a. An increase of the distance between the centre of the platform and the centre of the large columns will change the factor $f_{(m)}$, used in section 4.2, a little (see figure 21).
The decrease of the wave exciting force for frequencies lower than $\omega = 0.8$ sec^{-1} is very small.
The increase of the wave exciting force for frequencies larger than $\omega = 0.8$ sec^{-1} has little effect since at these high frequencies the heave response due to wave excitation is negligible.

b. An increase of the added mass by increasing the diameter of the footings at a constant displacement causes a small decrease of the natural period of the heave motion, which decreases the response function for the frequencies of most waves.

c. An increase of the diameter of the footings at a constant displacement causes an increase of the vertical wave exciting force due to the added mass. For low frequencies $\omega < \omega_m$ the vertical wave exiciting force will decrease while for frequencies larger than ω_m the wave exciting force will increase. The results of increasing the diameter of the footings will be more favourable for the smaller water depths. For the smaller water depths, however, this increase will change the wave exciting force to a smaller amount than in deep water.

d. An increase of the height of the footings at a constant displacement will decrease the wave exciting force for frequencies larger than ω_m. Again a small effect will be obtained at shallow water though this effect is more favourable at shallow water than at deep water.

When combining point b, c and d it may be concluded, that a decrease of the diameter of the footings causes smaller heave response functions at deep water.

When for instance the diameter is reduced to 18 m, the wave exciting force at $\omega = 0.5$ sec^{-1} will decrease about 25% and at $\omega = 0.6$ sec^{-1} about 20%.

The virtual mass $A_{\bar{z}\bar{z}}$ will decrease about 3%.

If the natural period of heave has not to be changed, the diameter of the upper part of the column has to be decreased a little (about 1½%).

In order to have the displacement of the platform unchanged when the diameter of the footings and of the column is decreased, one can increase the effective height of the footings. By means of the above-mentioned small modifications, heave at deep water can already be reduced by an amount of 25%.

5 Conclusions

It may be concluded that the approximation of the hydrodynamic coefficients and the wave exciting forces is backed by the results obtained from model tests.

This result is of importance for a theoretical determination of the optimum dimensions of the platform of given configuration from a point of view of the behaviour of the platform in a seaway. This aspect is the aim of a further study which has been initiated since the hydrodynamic properties were known.

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Fig. 11a-11e. Added mass (p_{mn}) and damping (q_{mn}) coefficients.

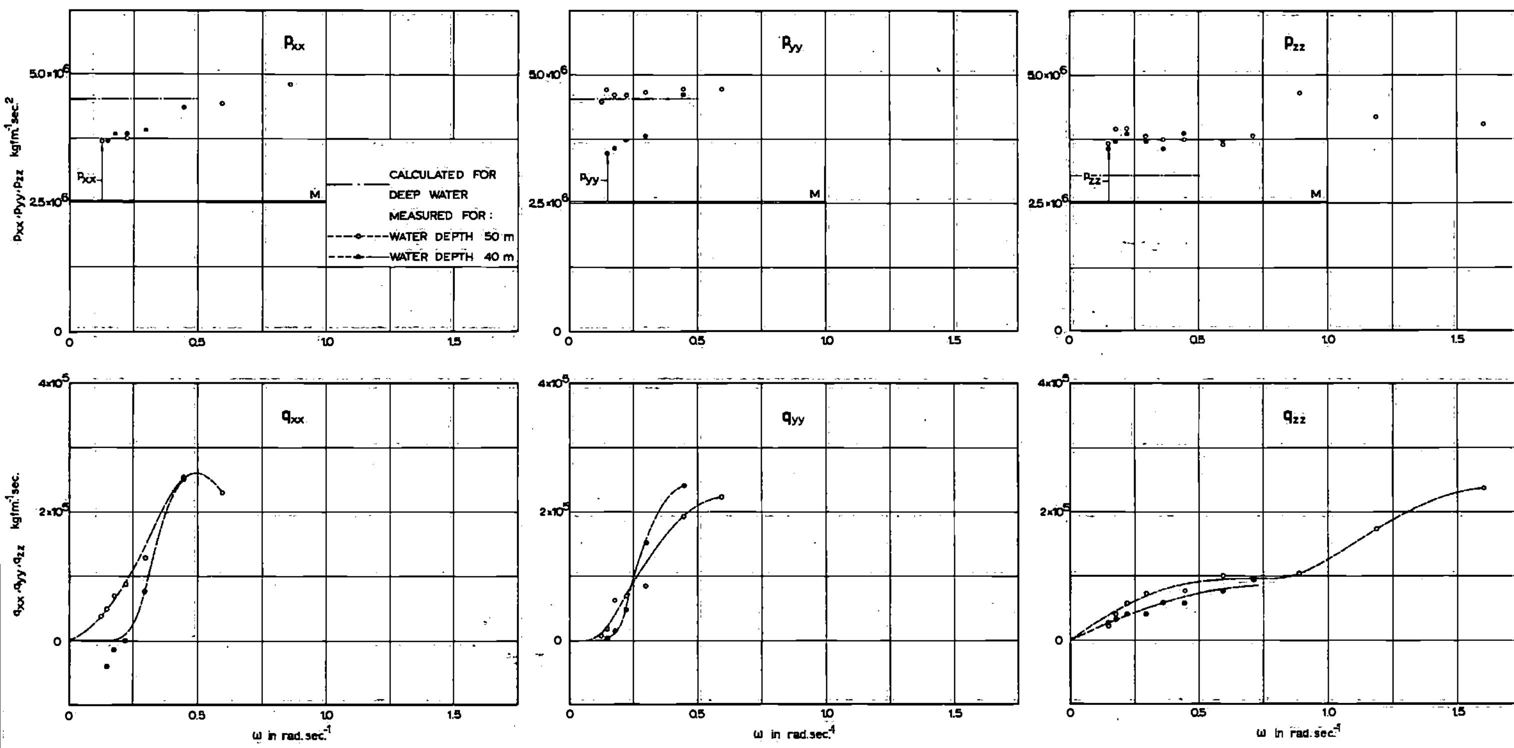

Fig. 11a.

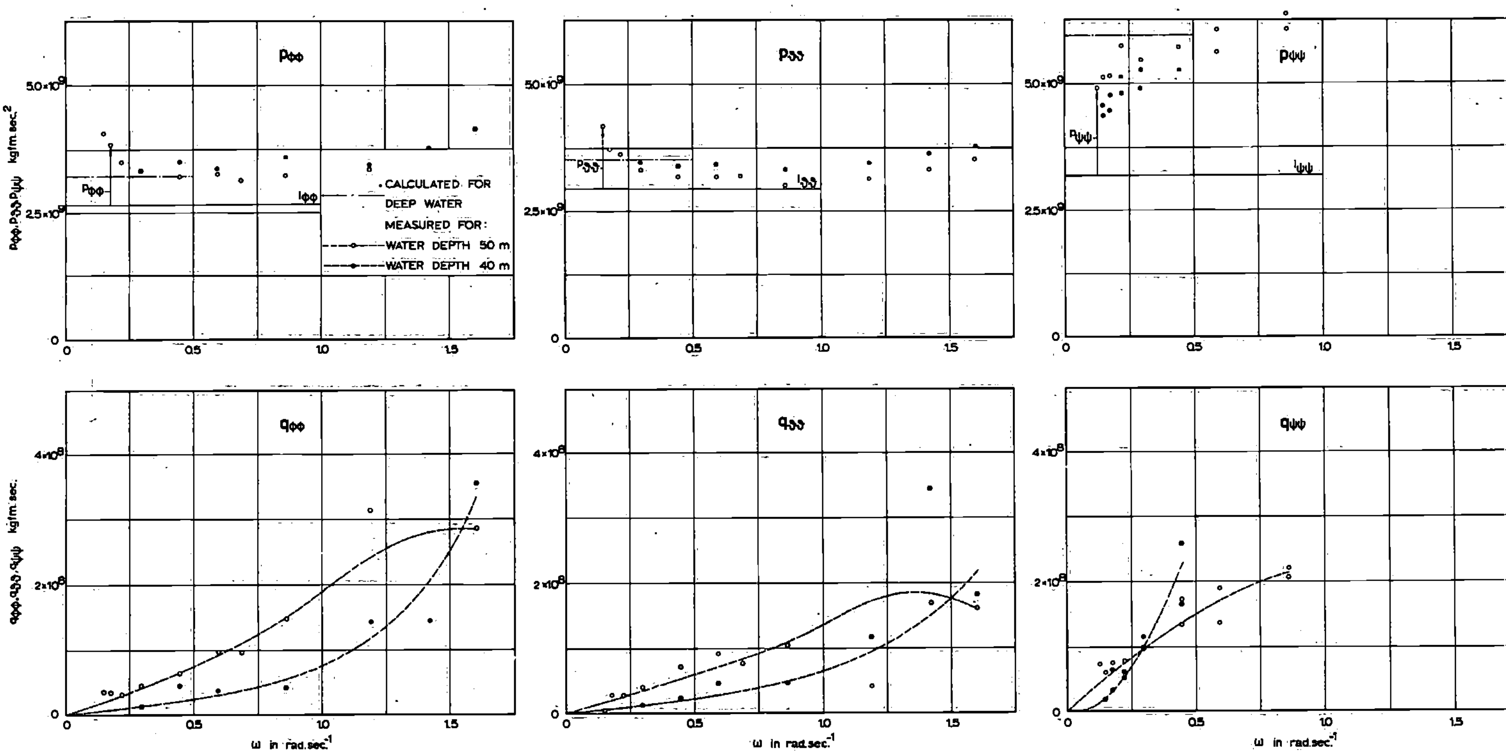

Fig. 11b.

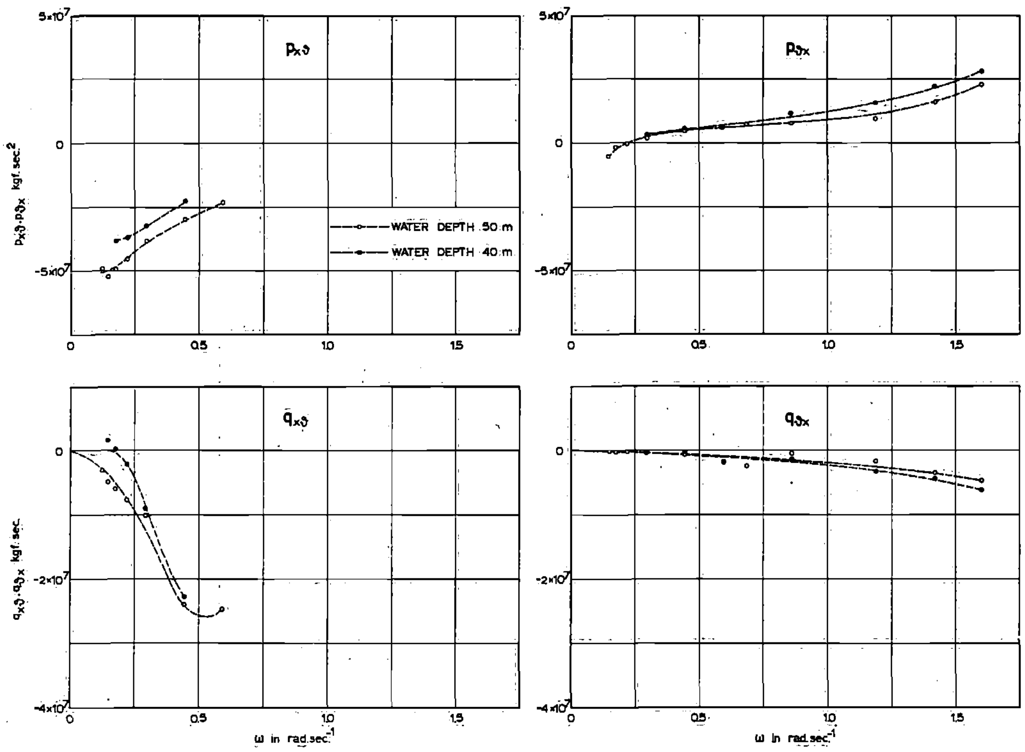

Fig. 11c.

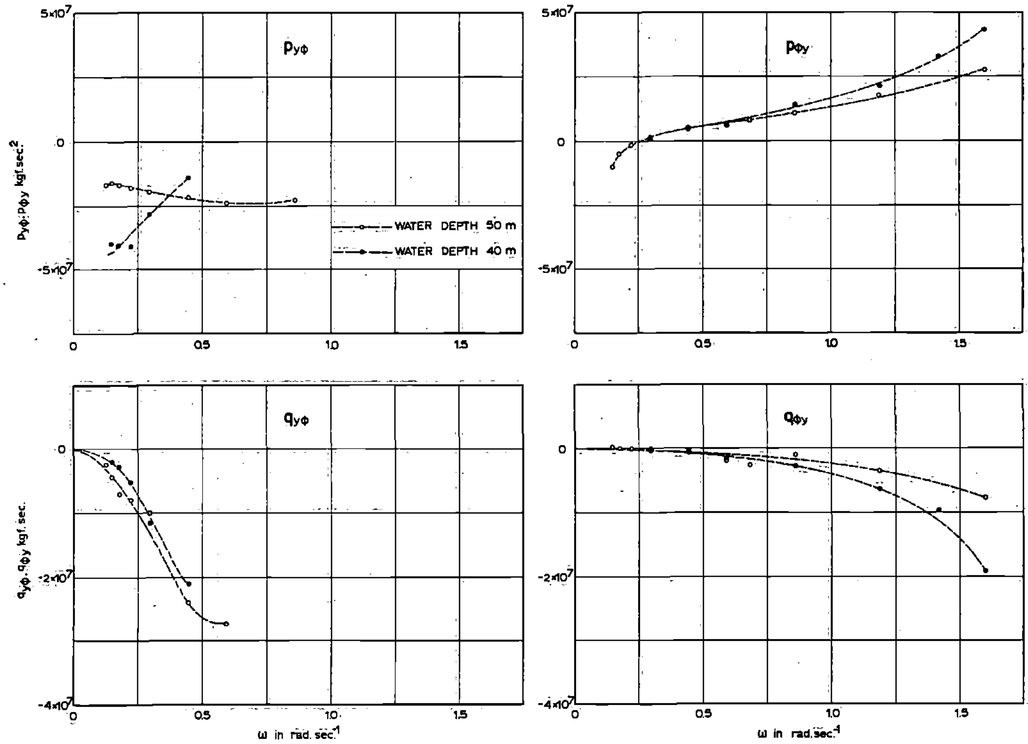

Fig. 11d.

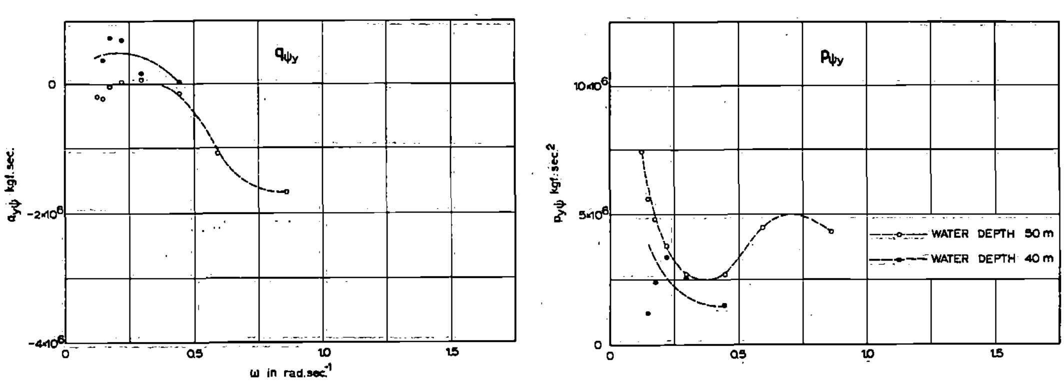

Fig. 11e.

Fig. 12a-12c. Wave exciting forces and moments on the platform.

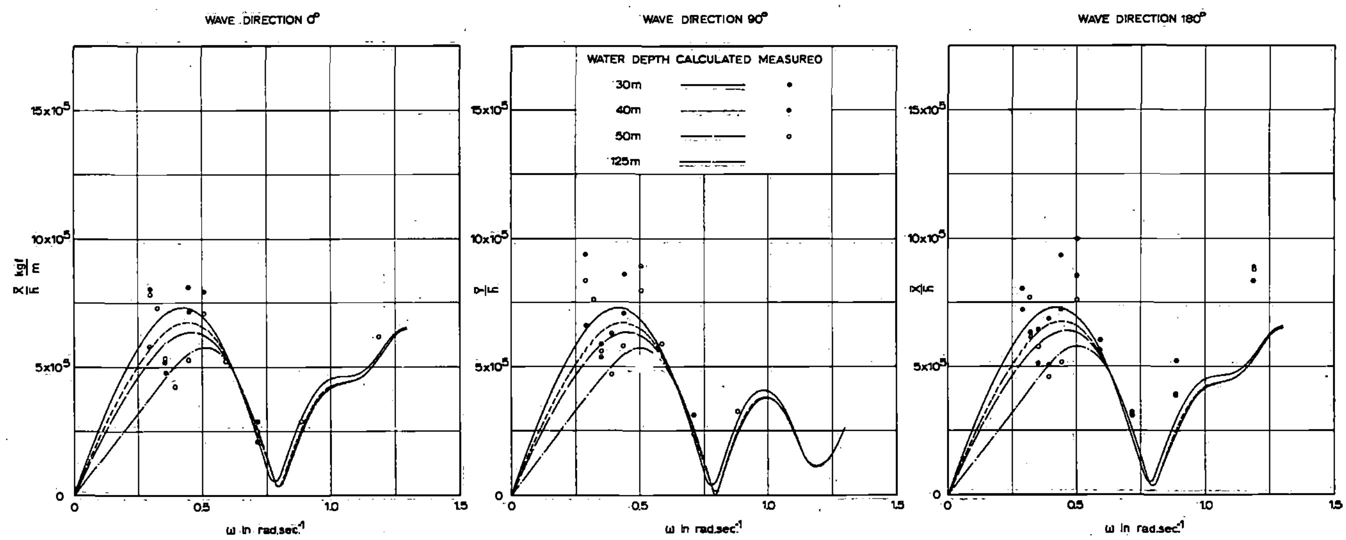

Fig. 12a.

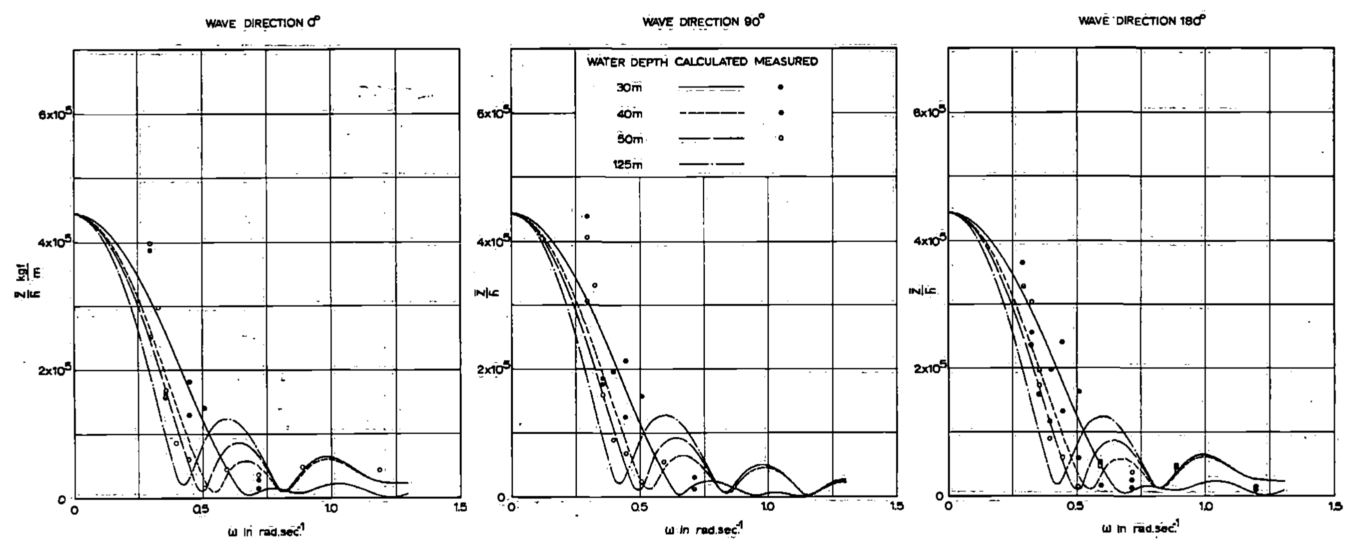

Fig. 12b.

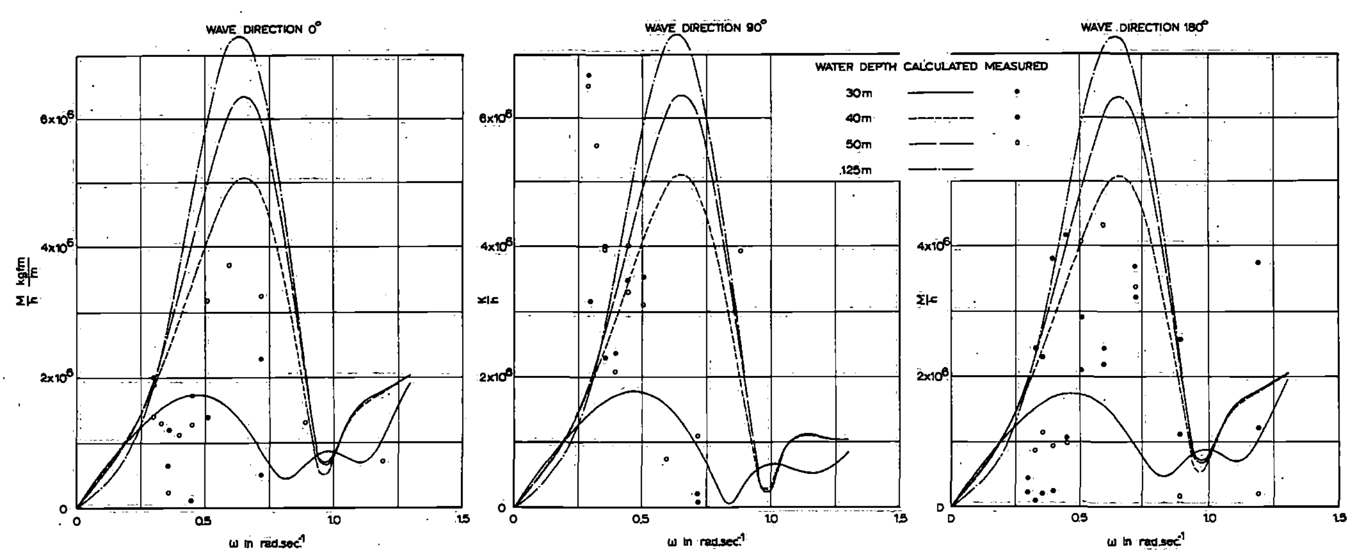

Fig. 12c.

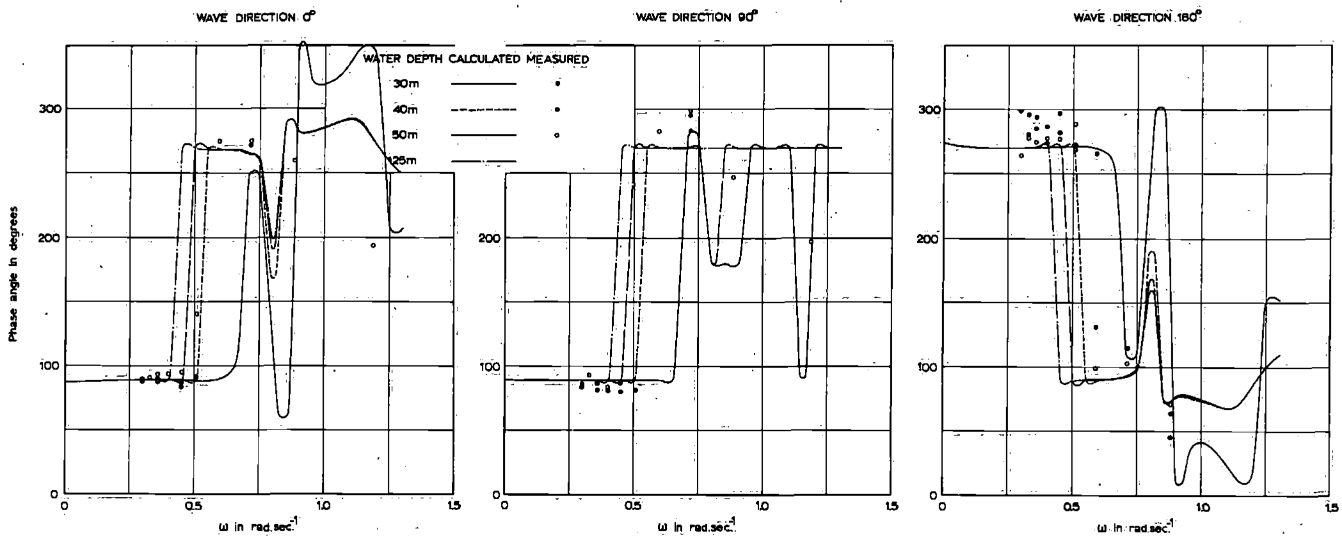

Fig. 12d. Phase difference between vertical and longitudinal (0°, 180°) or lateral (90°) wave exciting force (Positive when longitudinal or lateral force is ahead).

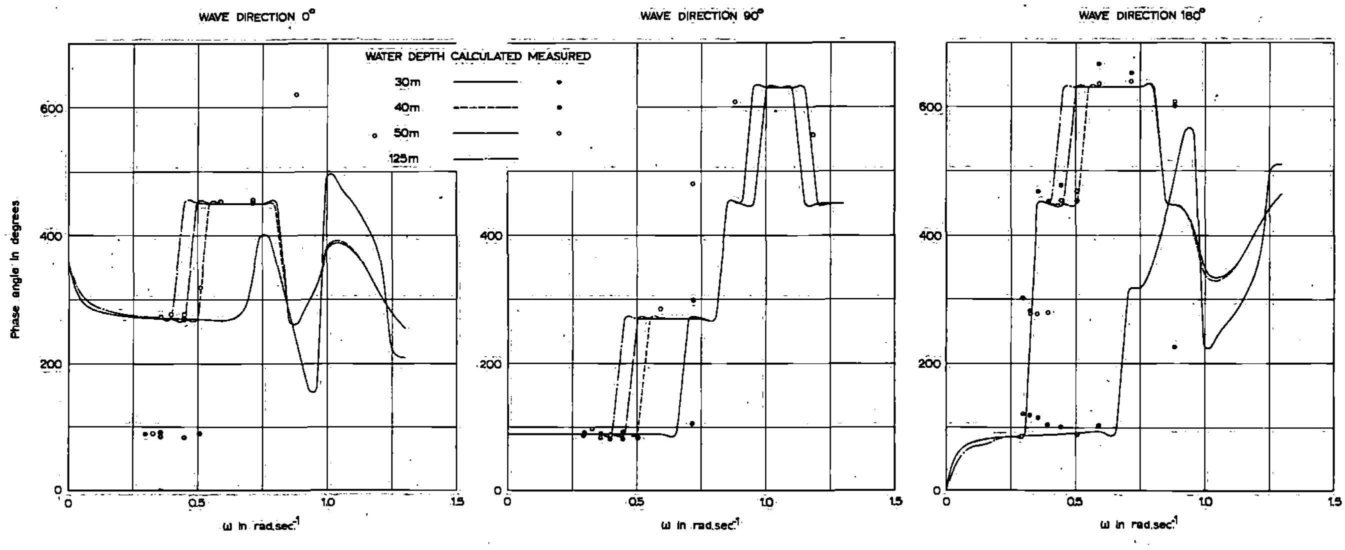

Fig. 12e. Phase difference between vertical force and pitching (0°, 180°) or rolling (90°) wave exciting force (Positive when pitching and rolling moment is forward and to starboard respectively).

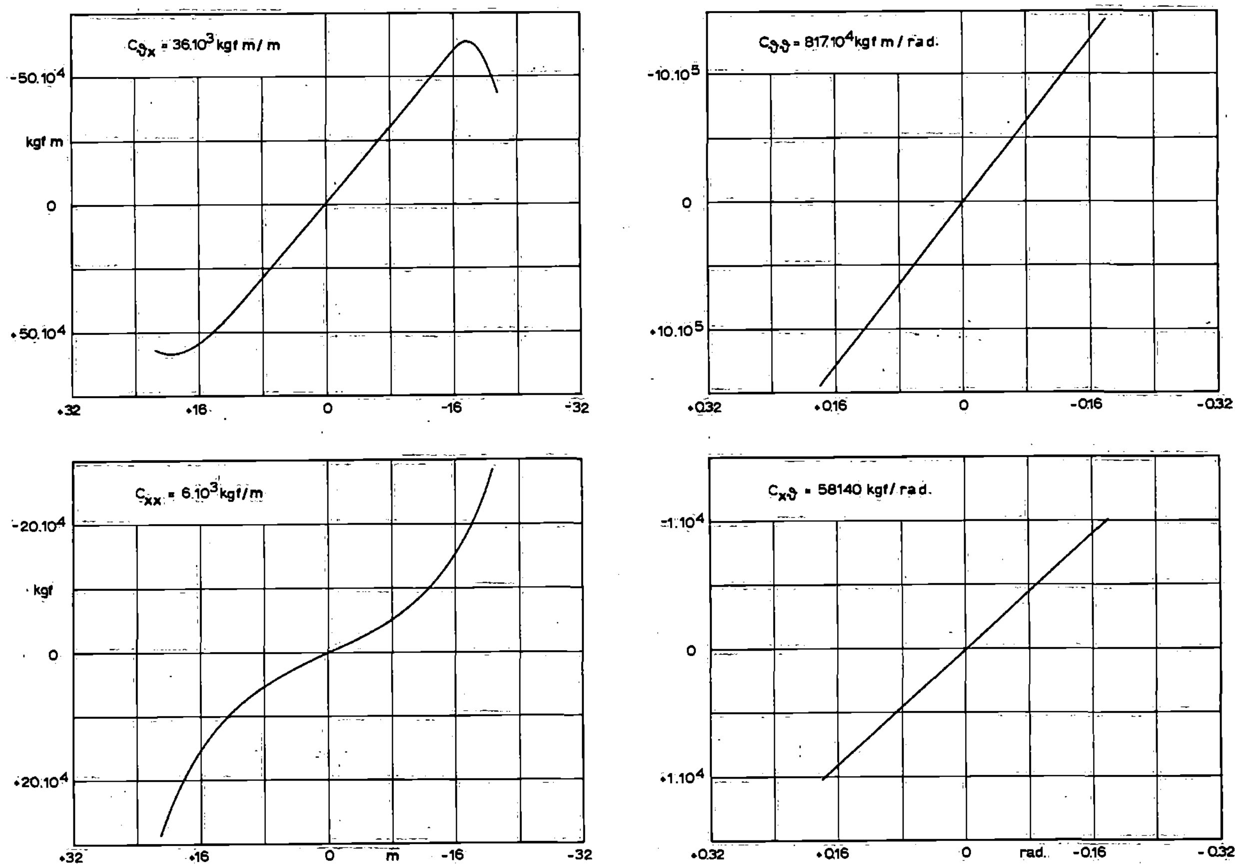

Fig. 13. Horizontal elasticity of anchor system

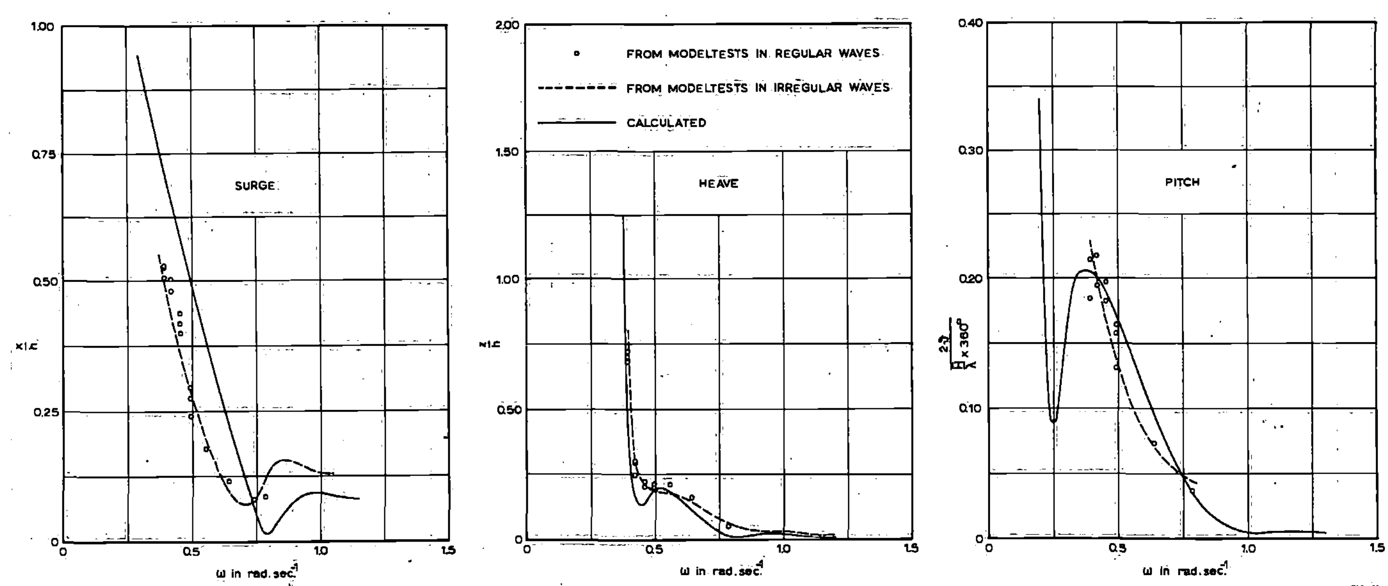

Fig. 14. Response functions of tests in regular waves and irregular waves at a water depth of 125 m

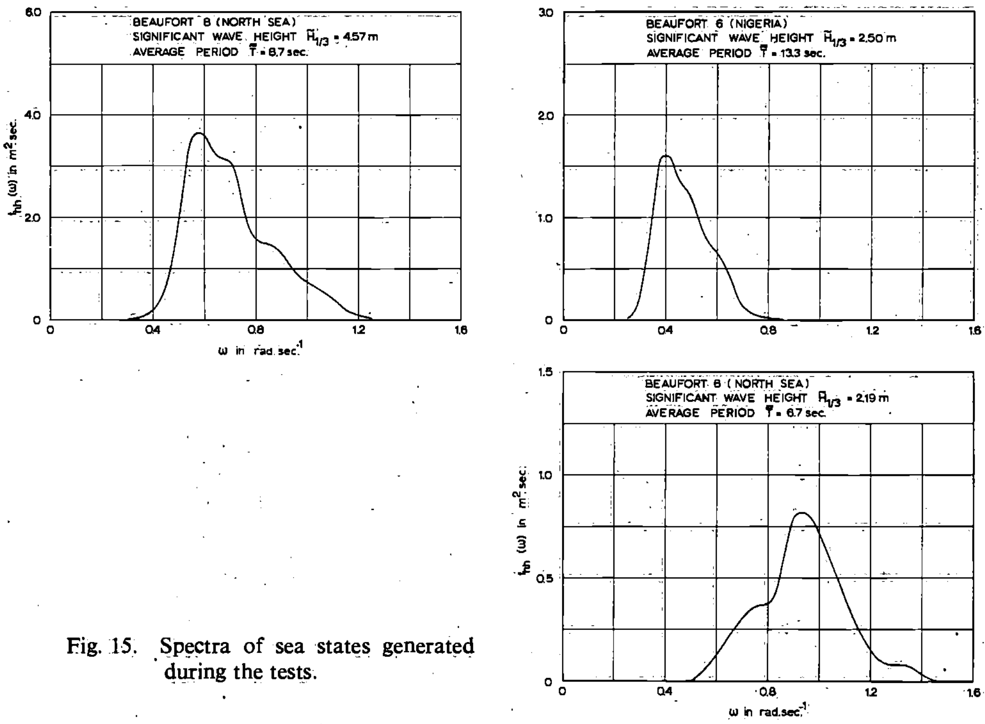

Fig. 15. Spectra of sea states generated during the tests.

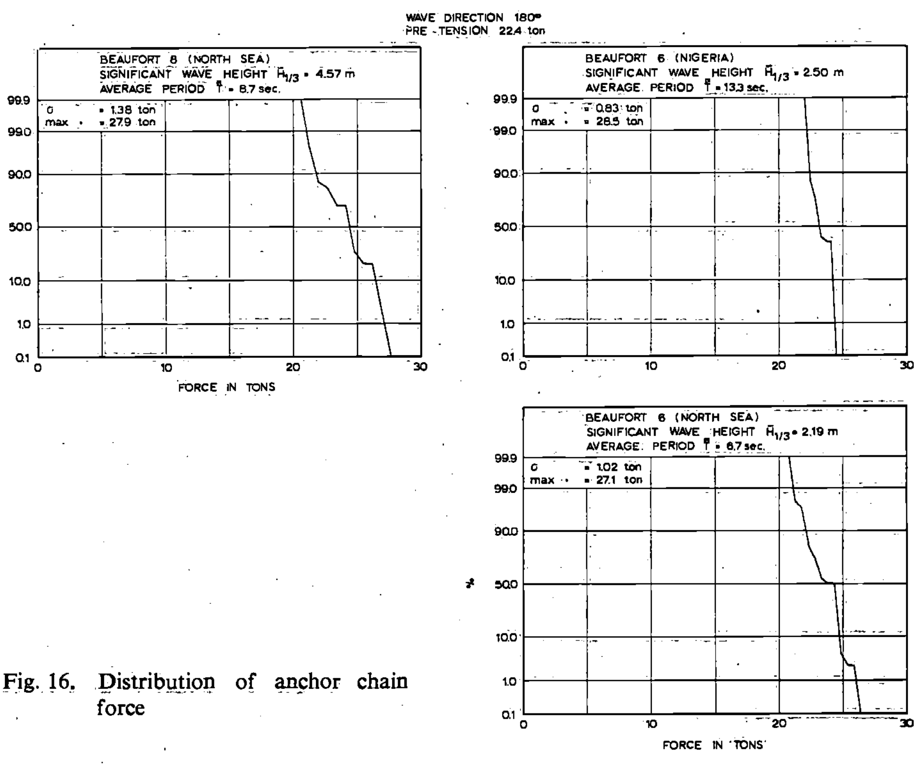

Fig. 16. Distribution of anchor chain force

$$\mu_1 = \frac{\cosh . m(d + \zeta)}{\cosh . m . d}$$

d = WATERDEPTH

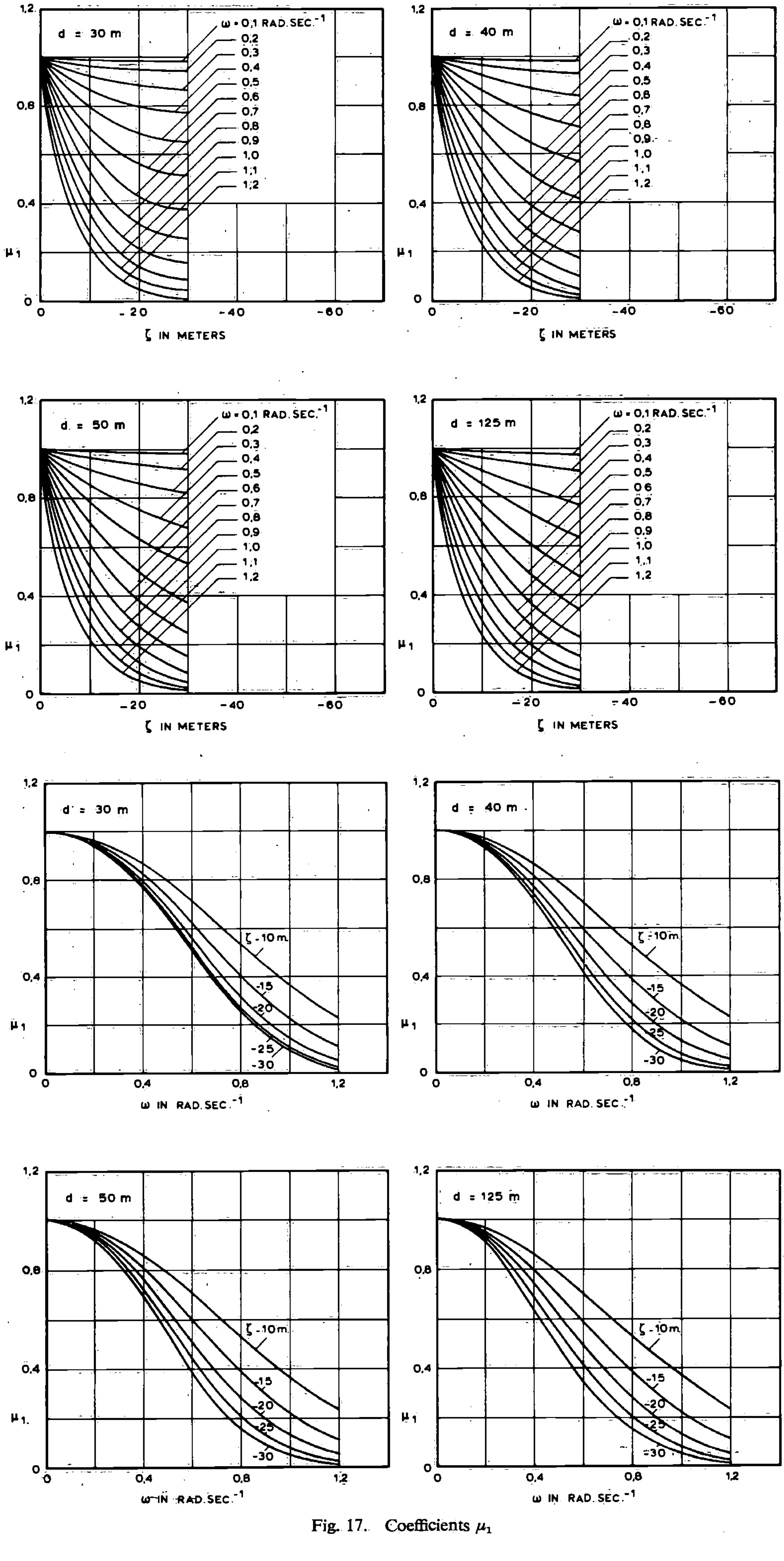

Fig. 17. Coefficients μ_1

$$\mu_2 = \frac{\sinh . m (d + \zeta)}{\sinh . m . d}$$

d = WATERDEPTH

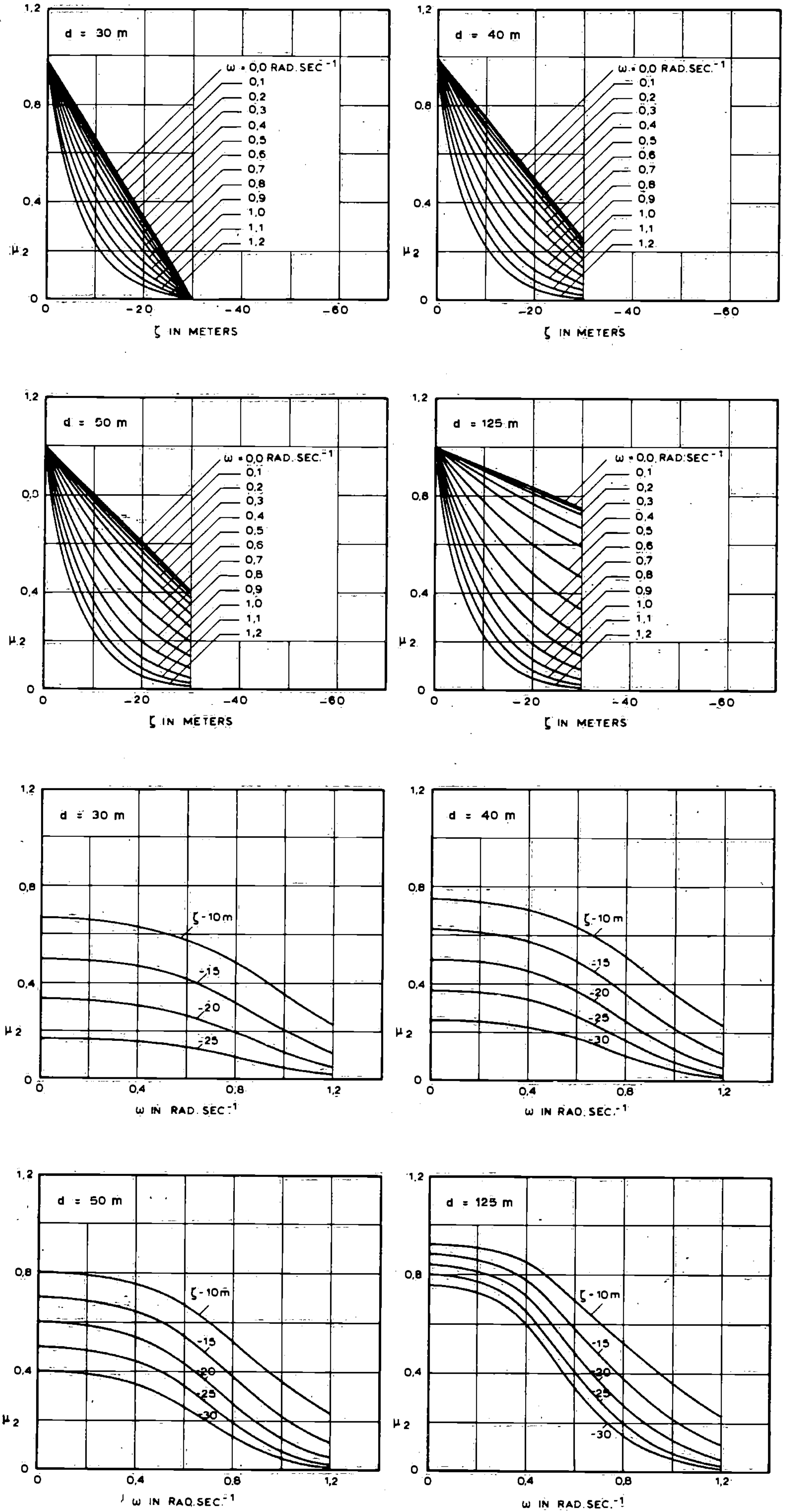

Fig. 18. Coefficients μ_2

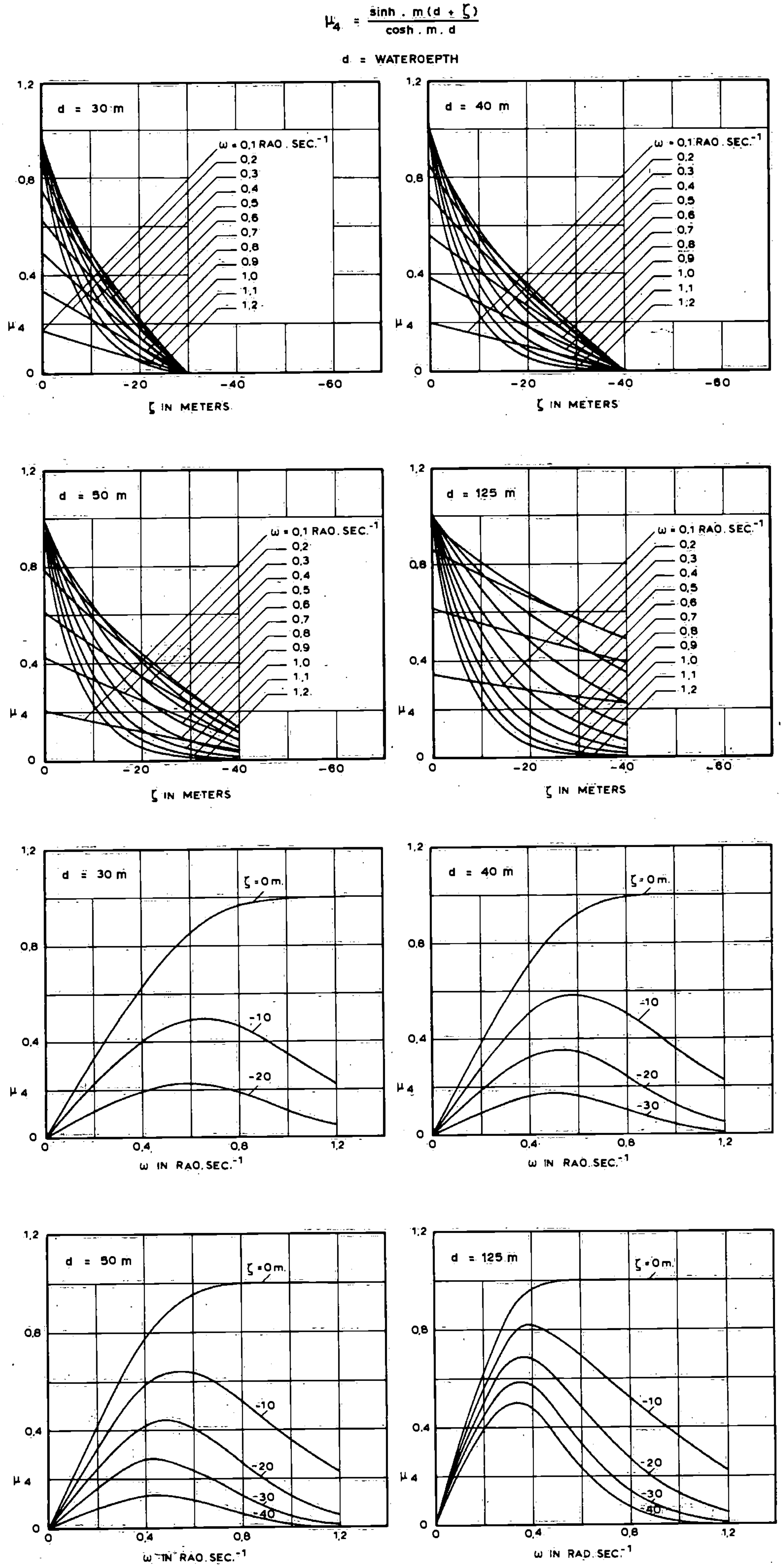

Fig. 19. Coefficients μ_4

$$\mu_5 = \frac{\omega \cosh . m (d + \zeta)}{\sinh . m . d}$$

d = WATERDEPTH

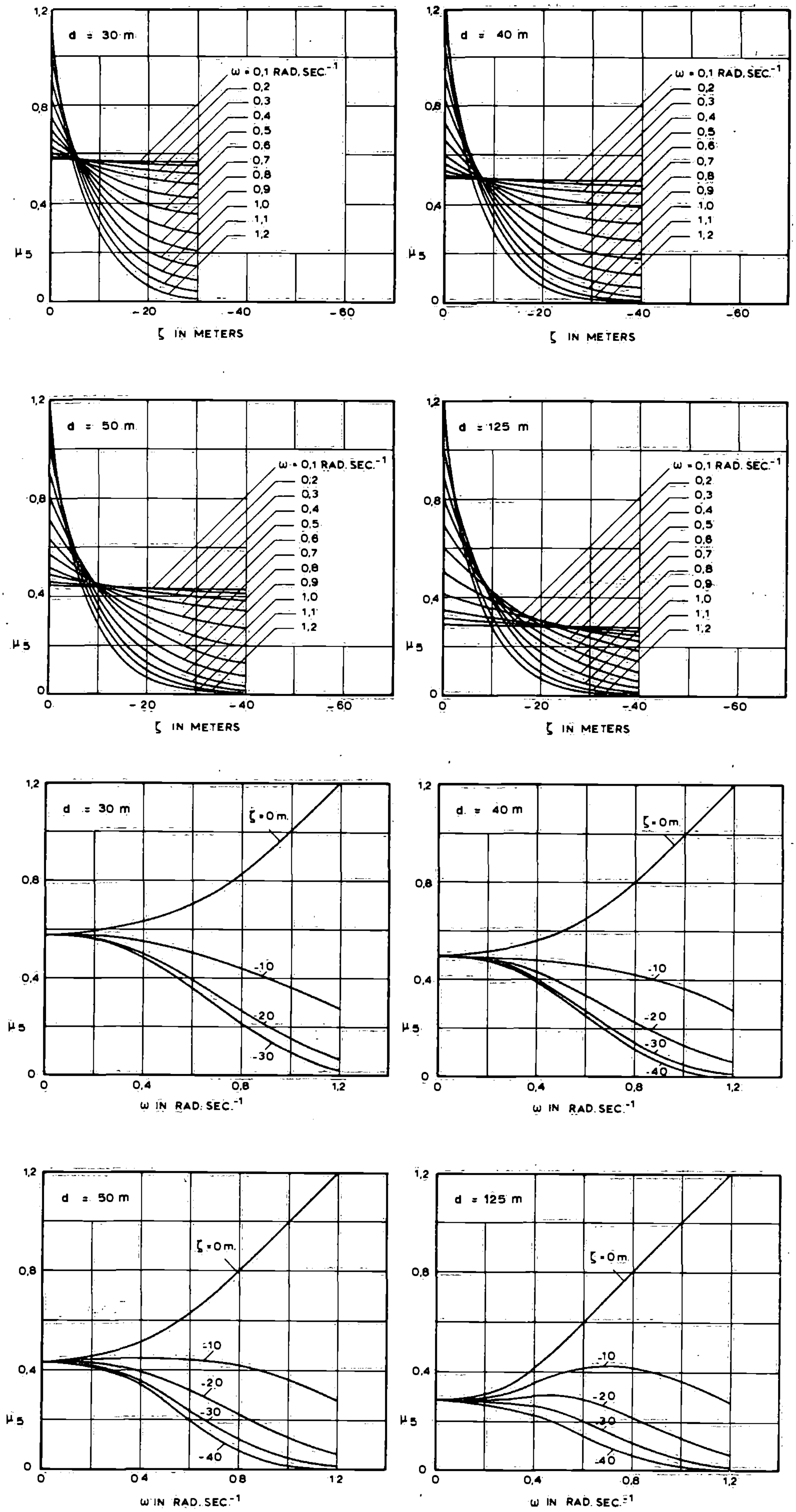

Fig. 20. Coefficients μ_5

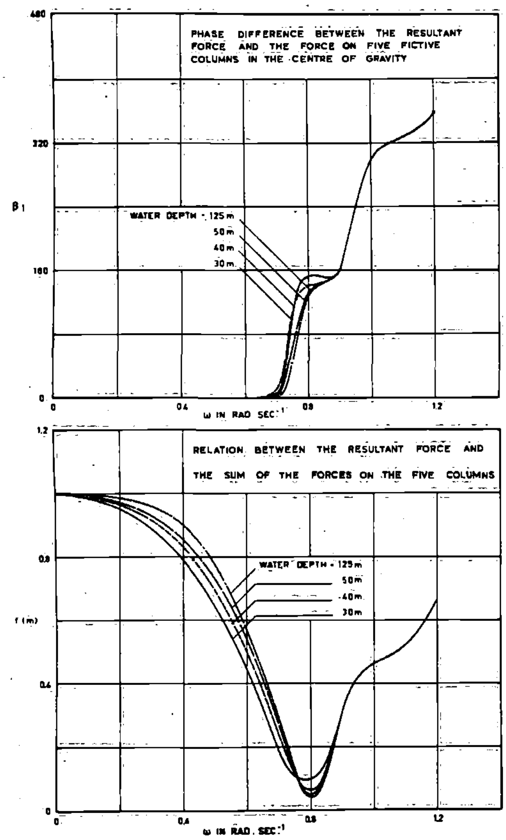

Fig. 21. Relation $fe^{i\beta_1}$, between the resultant force and the force on five fictive columns in the centre of gravity of the platform.

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