II-2 THE STUDY OF THE MOTION OF SEA-GOING VESSELS UNDER THE INFLUENCE OF WAVES, WIND AND CURRENTS, IN ORDER TO DETERMINE THE MINIMUM DEPTH REQUIRED IN PORT APPROACHES AND ALONG OFF-SHORE BERTHING STRUCTURES FOR TANKERS AND ORE-CARRIERS

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1. INTRODUCTION

With the increasing diepgang draught of tankers and bulk carriers the distance from the oil terminals and the wharves to the depths in the seas where these ships can move safely about is also increasing. This requires extensive dredging operations in the long approach channels and the determination of the minimum safe dimensions of these channels becomes a topic of high economic value. At places where dredging and maintaining of approach channels would not be an economic proposition and accommodation for mooring, loading and unloading in open sea is in use, the minimum depth requirements at the berthing site are also of main importance as the cost of the submarine pipeline forms a major part in the total costs. The minimum depth requirements for the approach channels and the off-shore berthing sites are related to the vessel's motion relative to the sea surface, the height of which again varies with respect to the sea-bed owing to the tides and wind effects.

Consequently the position of the vessel with respect to the sea-bed is determined by three factors, namely:

a. the height of the water level undisturbed by waves (astronomical tides plus wind effect);
b. the position of the deepest point of the moving vessel on restricted water (draught plus squat); and
c. the movement of the extreme points of the vessel's romp hull as imposed by the water movement due to waves (roll, pitch stampen and heave).

The factors mentioned under (a) and (c) have a statistical character as they are closely related to the meteorological conditions which in most cases can be regarded as a stochastical phenomenon. When introducing such a statistical consideration, for each possible depth of the fairway or berthing site a probability or chance can be determined when it will be not safe for tankers of a certain size to make use of it. When comparing the losses due to these delays with the extra costs required for obtaining a greater depth, a decision can be made about the criterion to be adopted.

In this paper we will not consider the economic aspects of this decision problem, because they depend very much on the local conditions, but we will confine ourselves to the statistical and hydraulic aspects and discuss a method of deriving the relation between a certain depth and the risk of unsafety.

2. THE HEIGHT OF THE WATER LEVEL UNDISTURBED BY WAVES

2.1. Astronomical tides

The variation in sea level caused by astronomical tides is usually a predictable quantity. But as it is determined by such a great number of harmonic bestanddeel constituents this proportion of the variation of the sea level may be regarded as a stochastical phenomenon. The cumulative probability distributions of astronomical high and low water levels (computed, for example, for the North Sea reference tide gauge at the Hook of Holland) are indeed almost gaussian (see Fig.1).

The probability distribution curve C in Fig.1 represents all the water levels and is deduced from the distributions of high and low water levels using the shape of the mean tidal curve for the Hook of Holland. vorm

The climate in the North Sea area is unstable during the whole of the year, there is no systematic seasonal influence of the wind on the water levels. So in this area, the tidal constituents found by the tide gauge analysis are not correlated either with the wind effects or with the wave heights.

In regions with regular seasonal winds (passats for example), the effect of the wind on the determination of the components is not insignificant. The order of the correlation should be examined before the statistical laws are applied by combining the data on astronomical tides with the data on wind effects and on the wave heights.

2.2. Wind effect

The wind effect is defined as the difference between the predictable astronomical tide and the actual sea level. It can be computed for certain wind conditions using a method developed by Weenink [1] and others, for determining equilibrium sea levels in a partly closed shallow sea when both the wind force and its direction are unvarying. An example of computed wind effect as a function of wind direction is given in Fig.2. The wind effect is assumed to be caused by homogeneous wind fields in which the wind blows with force 7 Beaufort.

By this method, statistical wind data covering many years can be converted into statistical wind effect data. The results may be inaccurate, however, especially in areas with unstable wind climates.

For the North Sea this is evident when one compares the distribution curves of the wind effect computed by the "equilibrium method" with the actual wind effect; see Fig.3. There is a certain lag between the development of a wind field and the wind effect it produces. It depends on the dimensions of the sea.

Weenink [1] showed that the lag in the North Sea is about 6 hours (Fig.4) while the average time during which the wind blows in a certain direction is of the same order for wind forces above 6 Beaufort (Fig.5).

Consequently, the wind effect can be higher or lower than the equilibrium effect for more than one concomitant and identical wind observation, depending on whether the wind rises or falls. So a statistical distribution of the wind effect may be expected for every group of observations selected. If the groups are sufficiently small, the distributions will be gaussian.

Statistical sampling provided data on the wind effect for each of the 96 groups selected i.e. 12 classes of wind forces in each of the 8 wind sectors. Figure 6 gives some examples of such distributions. Where a sufficiently large number of observations within a group is available the distribution is indeed gaussian.

So a statistical distribution in each of the groups is determined in terms of a gaussian distribution that gives one of the straight lines in figure 6.

FIGURE 6

These statistical distributions form the basis for further computations and replace the function $W = f\ (V;\theta)$ found by Weenink [1] (in which W = wind effect, V = wind velocity, θ = wind direction).

Actual data for the groups with wind forces higher than 8 Beaufort are scarce. Therefore the distributions of the wind effect were computed for these groups from extrapolations of the data on wind effect with exceedance probabilities 0.1; 0.5 and 0.9 using the energy equation $W = C_{te}.V^2$ given by Weenink for the equilibrium wind effect (see examples on Fig.7).

FIGURE 7

The cumulative probability distributions of the wind effect for each of the 96 groups applied to the statistical data on the occurrence of the corresponding wind conditions covering a period of about 10 years form a basis for further statistical computations on the probability of occurrence of a certain state of the sea surface.

A final check on the reliability of the statistical sampling method is the fact that the resulting distribution curve of the wind effect in Fig.3 (marked with crosses) nearly covers the actual data.

3. THE POSITION OF THE DEEPEST POINT OF A MOVING VESSEL IN RESTRICTED WATER

When a tanker is moving forward through a channel, in which the horizontal clearance and the keel clearance is relatively small, she piles up ahead of herself a quantity of water that would otherwise occupy the space she is taking up. This amount of water then flows back along the ship's side and finally fills the corresponding volume remaining free astern; this is known as the return current. In accordance with Bernouille's theorem, the return current causes lowering of the water level around the vessel, relative to the free surface. The vessel is steaming in a trough that moves with her. This is one of the major factors contributing to squat which is in effect an additional sinkage of the vessel below her draught when stopped. This phenomenon has been studied extensively for the movement of ships in canals [2] [3]. However, the same hydraulic effect will occur if a ship is steaming in a shallow sea. The amount of squat is a function of the velocity of the return current; the greater the velocity the greater the squat, resulting in a greater decrease of under keel clearance. Similarly, the squat will be greater

a. if the ship is steaming in more restricted water and
b. if the speed of the vessel is greater.

A second factor that contributes to squat is the wave (bow and stern) pattern around the ship when moving.

The variations in water surface due both to the fall in water level and the wave pattern usually also effect the ship's trim.

3.1. Model tests

Sogreah Laboratory in Grenoble

Société Maritime Shell on behalf of the Royal Dutch Shell Group requested the Sogreah Laboratory in Grenoble to carry out model tests in order to determine the squat of tankers its relation with the depth, width and bank gradient of the channel and the draught, beam and speed of the ship (6 parameters).

The model ship was a 1:40 scale model of a 70,000-ton tanker. It has been assumed for the practical application of the test results that this ship model could represent tankers of other sizes to different scales.

In order to cover all variations of channel shape several ratios were varied:

(1) Ship cross-section to channel cross-section;
a number of bank gradients were investigated; the bottom width of the channel was varied from 1.5 to 9.8 times the beam of the model. The conditions of the ratio 9.8 differ only slightly from those found in open water where the width is practically unlimited.

(2) Depth of channel to draught of ship;
a number of channel depths and ship's draughts were employed, giving ratio values of 0.04 to 1.82.

diepte [illegible] = 0,04 → [illegible] = 0,04 x diepte
[illegible] 1,82 → diepgang [illegible]

(3) Mean width of channel to breadth of ship; the value of this ratio was varied from 2.3 to 9.8.

Now the relationship can be found between the squat of a model of given beam and the five main variables: speed, draught, depth of channel, top width and bottom width of channel.

For general use of the results of the model tests a graphic method was produced, [4] shown in Figures nos.8 and 9. The first graph (Fig.8) gives a limiting or critical velocity, V_L, as defined by Schijf [2], [3]: $\frac{V_l}{\sqrt{gH}} = f\left(\frac{s}{S}\right)$

where,

H = mean depth
s = midship area of vessel
S = cross-sectional area of channel.

The second graph (Fig.9A) represents ratio of maximum squat value and mean channel depth $\left(\frac{Z_{max.}}{H}\right)$ as a function of the ratio of forward speed and Schijf's "limiting velocity" $\left(\frac{V}{V_l}\right)$ for several values of $\frac{P}{t}$ (P = depth of the centre part of the channel; t = ship's draught). Figure 9B gives a correction factor for a range of values of the horizontal clearance ratio $\frac{L}{B}$ (L = the mean width of the channel and B = beam of the ship).

Limiting factors of these graphs are:

(a) vertical clearance ratio, $1.10 < \frac{P}{t} < 2.80$

(b) horizontal clearance ratio, $2.30 < \frac{L}{B} < 10.00$

(c) the canal bank slope should only be slightly deviating from the gradient of 1:3, at least for narrow channels.

The above-mentioned model tests were devoted to trapezoidal sections. One of the most common forms of natural channels has a practically unlimited water surface but a depth only a little greater than the vessel's draught; for example, a tanker that crosses more or less unrestricted shallow water in the approaches to a port.

Tests have shown that for practical purposes in open water circumstances a channel width (wide-channel condition) of ten times a ship's beam may be used; although the results will be somewhat too unfavourable.

Using the graphs 8,9A and 9B Figure 10 has been derived which gives the relation between squat and speed for two tankers (20,000 t (dw) and 35,000 t (dw)), steaming through channel with a water depth of 42 ft.

The curves I (unlimited channel or L =10 B) and III fully banked channel have been found directly from the graphs mentioned above.

The curves II refer to a channel with the form of a deep trench (42 ft) with berms on either side (21 ft). Investigations a this type of channel [4] showed that for practical purposes an approximation may be made to the squat of a vessel passing through such a channel.
Firstly, the problem is solved for a tropezoidal canal section disregarding the berms (curves III), secondly the squat is calculated for a rectangular channel section of the same depth and extending the full width of the berms or 10.B (curvesI). These two results are then meaned proportionately to the ratio of berm depth to channel depth; in order to give curves II.

Netherlands Ship Basin Laboratory (N.S.P.)

In connection with the design of the new harbour entrance near Hook of Holland (Europoort) the Rijkswaterstaat asked N.S.P. to carry out model tests in order to find the maximum squat of big tankers in waters with relatively small depth and practically unlimited width.

The vessel used for these tests was a scale model (1:40) of a tanker of 100,000 tons deadweight (breadth 41.15 m; draught 15.24 m). It is assumed that this model is also representative for various sizes of tankers on other scales.

Squat measurements were made of tankers' bow and stern squat for a range of ships' speeds and ratios of water depth to draught $\frac{p}{t}$ = 1.1, 1.2 and 1.4. It was found that maximum squat generally appeared at the ships bow.

The results of these investigations were embodied in a graph (Figure 12) representing $\frac{p}{t}$ curves as a relation between dimensionless values of $\frac{Zmax.}{H}$ and $\frac{V}{\sqrt{gH}}$.

A corresponding curve for $\frac{p}{t}$ = 1.25 was determined by the Sogreah Laboratory method. This curve has been drawn in Fig.11 and shows good agreement with the curves of N.S.P.

3.2. Squat measurements in nature

Maracaibo Deep Channel

Under the sponsorship of the member companies of the Marine Conference, squat measurement of tankers were made in the Maracaibo Deep Channel in 1958 and 1959.

Squat was determined by means of a echo-sounder; the projector, pointing upwards, was placed on the channel bottom (in the fairway) and connected by a cable to the recorder outside the fairway (method: "echo-sounder in reverse").

After the passing of a tanker the recorder trace gave the following information:

1. Depths of water;
2. under-keel clearance and
3. trim of the vessel.

Taking into consideration the draught of the vessel when stopped, the bow and stern squat could be found.

During squat measurements the ship's speed was determined.

Observations took place at three parts of the channel, viz:

a. Inner part of the channel: bottom depth 37½ - 39 ft., width 600 ft.; tankers 16,000 - 19,000 t(dw.) and 25,000 - 28,000 t(dw.).
b. Outer part of the channel (wide channel conditions): bottom depth 43 - 44 ft., width 1,000 ft.; tankers 16,000 - 19,000 t(dw.) and 25,000 - 28,000 t(dw.).
c. Outside channel breakwater (open seas (wave) conditions): bottom depth 38½ - 42½ ft.; tankers 16,000 - 19,000 t(dw.) and 35,000 t(dw.).

Figure 12 gives the results (points of the measurements for tanker in 25,000 - 28,000 tons class, mentioned under b compared with the curve representing maximum squat according to model tests for the same conditions.

Rotterdam Waterway, Deep Channel

Rijkswaterstaat, in cooperation with Shell and Esso, has been measuring the squat of tankers in the 35,000 - 90,000 tons class in the deep channel leading to the entrance of the Rotterdam Waterway (near Hook of Holland).

As in this channel trailing-dredging is permanently in progress, the method "reversible echo-sounder" cannot be used here, and another method had to be chosen. So the observations are made by means of levelling instruments mounted on the end of the North breakwater. By these instruments, to which a camera can be linked, the level near the bow and stern of the vessel, when moving, are levelled, namely,

a. With the aid of specially-designed staffs mounted on the ship's superstructure (reading or/and photos) and
b. by photographing significant parts (windows, etc.) of the vessel's superstructure.

The level of these staffs and significant parts of the ship relative to the water level (undisturbed) is known. This water level is recorded and depth of the channel bottom can be taken from soundings. During the levelling the tanker's speed is measured.

So bow and stern squat, at various speeds and ratios of draught to depth, can be determined by taking into account the ship's draught (for and aft) when stopped.

As an example, the results of a squat measuring of the 77,148 - ton Shell tanker "Sitala" (breadth 38 m; draught 13,9 m) has been plotted on Fig.12 against the ship's speed, and this coincides with the corresponding squat curve taken from the model tests.

4. THE MOVEMENT OF THE EXTREME POINTS OF THE VESSELS HULL AS IMPOSED BY THE WATERMOVEMENT DUE TO WAVES

If the water surface is disturbed by wave action the vessel is moving under influence of these waves. There are three components related to the matter in hand.
Heave is the vertical motion of the centre of gravity of the ship. If no other motions are present this is equivalent to an up and down motion of the whole ship. Roll is defined as the angular motion around the longitudinal axis through the centre of gravity and pitch is the angular motion around the athwart ships axis.
The amplitude of the motion of the extreme points of the vessels hull is influenced by the dimensions of the ship and the state of the sea which can be defined for each wave direction by wave height and wave period.

4.1. Description of the state of the sea

The state of the sea can be described by the wave spectrum that describes mathematically the distribution of the square of the wave height (wave energy) with period.
The most desirable method to obtain such spectra is by analysis of local measurements. If such measurements are not available the spectra must be estimated from observation of wave heights and periods.
In this example long crested irregular seas are used instead of short crested seas for the case of simplicity.
Figure 13 gives the relation between observed wave height and observed wave period on the North Sea [5].
For each Beaufort number the average observed period has been plotted on base of the wave height. A line drawn through these spots gives the relation between observed period T_W and wave height H used in the wave spectra.
Figure 14 shows the form of these wave spectra which are in this example used for the subsequent determination of the ship motions.
They are of the Neumann type and defined by:

$$f(\omega) = \frac{C_1}{\omega^6} e^{-\frac{C_2}{\omega^2}}$$

where ω is the wave frequency in radians per second.
The values of C_1 and C_2 are selected in such a manner that the significant wave height is equal to the observed height and the average period of the zero upcrossings is equal to the concomitant observed period.

If this procedure of estimating the wave spectrum is followed, each value of the significant wave defines one specific spectrum.

A method analogous to the sampling method described in the previous chapter was adopted in this example to determine the statistical distribution of significant wave heights.

The only difference is that the linear function $H = C_{te}.V$ (Fig.15) was used for the extrapolation of the relation between the wind data and the wave heights instead of the quadratic function used in Fig.7.

Since H^2 is proportional to the energy of the waves, this linear relation satisfies the energy relation again. The significant wave height distributions are also almost gaussian for most of the 96 groups of wind conditions (see Fig.16).

FIGURE 16

For the higher wind forces (10 Beaufort and more), however, linear extrapolation gives the lines that seems to deviate from the observation (points in Fig.16).
However, the number of observations is so small, that the gaussian distribution computed with the aid of the linear extrapolation in Fig. 15 may also be accepted for further computations.

4.2. Combination of parameters determining the critical sea surface conditions

The previous section indicated that the necessary overdepth depends partly on the motions of the ships entering the harbour. These motions are influenced by the dimensions of the ship, wave height, wave period and wave direction. Moreover both ship motions and waves are influenced by the waterdepth.
Therefore it is necessary to make a rough estimate about the required waterdepth beforehand. At present it is still considered impossible to calculate ship motions on shallow water and therefore direct measurements on ship models are required. When the model experiments are conducted in various regular wave conditions the results can be used to determine the probability of the occurrence of large deviations under a certain weather condition, provided the wave spectrum of this weather condition is available.
Because of the stochastic character of the ship motions no absolute maximum amplitude exists, and a maximum acceptable probability of bottom contacts has to be determined.

As stated before, the astronomical tide can often be regarded as a stochastical phenomenon which is independent on the other factors caused by wind: the windeffects and the wave heights.

The correlation between significant wave heights and wind effect for concomitant wind data is found to be weak in the North Sea, in spite of the fact that the waves are mostly generated by the wind field that causes the wind effect.

For example, the correlation coëfficient obtained from 136 observations of both significant wave heights and wind effects was found to be 0.02 for the same group of wind data: wind force 7, wind direction NW. So there is no significant correlation at all within such a group.

This apparent illogicality is partly due to the difference between the lag of the wind effect being 6 hours, (see previous chapter) and the observed lag of 2 or 3 hours in the changes in the wave heights due to by increasing wind.

So the basic statistical laws on summons and products of combined probabilities may be applied combining all three factors: the astronomical tide, A, the wind effect W and the significant height H of the wind waves.

In respect to the ships movements:

pitch, roll and heave, the significant wave heights H have to be reduced to the significant amplitude $\frac{1}{2} H_s$ of the ships movement by a response factor $\bar{\alpha}$ so that $\frac{1}{2} H_S = \frac{1}{2}\bar{\alpha} H$. As long as there are not sufficient data on the $\bar{\alpha}$ values. This coefficient is taken for variable.

The necessary over depth ζ is determined by:

$$\zeta = A + W - \tfrac{1}{2}\bar{\alpha} H + \text{squat} \qquad 4.1$$

and its probability of occurrence by:

$$P(\zeta) = P(A_i) \cdot P(W_j) \cdot P(H_k) \qquad 4.2$$

provided i; j and k are varying through all combinations of values that agree with equation 4.1 and provided both the probabilities of occurrence of the wind effects $P(W_j)$ and the wave heights $P(H_k)$ are derived from the same probabilities of occurrence of the wind.

The probability $P(\zeta)$ is evaluated separately for the following values of $\bar{\alpha}$:

$\bar{\alpha} = 0;\ \frac{1}{2};\ 1;\ 2$ in Fig.17.

FIGURE 17

This figure is the base for the decision in respect to the design criterion.

The actual level of the probability will have to depend on the soil conditions in the harbour entrance (a rock bottom will be more dangerous than a sandy bottom) and the type of ship (small ships will be relatively less vulnerable than large ones). Also the occurrence of density differences may play a role.

Interesting is the small variation of the difference between the curves $\bar{\alpha} = 0$ and $\bar{\alpha} = 1$ for all probabilities of occurrence $P(\zeta)$, so we can conclude, that in this case as long as the value of the response coefficient $\bar{\alpha}$ remains below 1, the real value is not of importance for decision problem.

4.3. Motions of a free moving vessel under the influence of waves

For the determination of the overdepth required by wave induced ship motions is illustrated here with the example of a 100,000 ton (deadweight) tanker on the North Sea.
The dimensions of this ship are as follows:

Length (between perpendiculars)	274.32	m
Beam	39.40	m
Draught (even keel)	15.24	m
Displacement	133,600	m^3

Response in regular waves

The vertical motion of any part of the hull can be computed once the three motions heave, roll and pitch and their mutual phase angles are known. However, because the accuracy of phase measurements offers some difficulties, it will often be more practical to determine the vertical motions directly for the critical points. Figure 18 shows the results of the measurement of the vertical motion of the bilge in a non-dimensional way. The experiment was conducted in beam waves at zero speed of the ship. From other tests it is known that this result will also be valid for speeds up to about 10 knots. For very long periods the wave slope approaches zero, so the vertical bilge motion becomes equal to the heave. Because the vertical motion of the center of gravity will be the same as those of the surrounding water in the long period waves, the non-dimensional bilge motions approache unity. The natural rolling period of this tanker is 14.6 sec. Therefore the largest bilge motions are found for waves close to that period, although the actual maximum occures at longer waves because of the increasing influence of the heave motion.
Figure 19 gives the vertical bow motion. in head and following waves. These results belong to the tanker going with a speed of 8 knots in water of a depth of 1,2 times the draught, that is 18,28 m.
In this case the period of encounter between ship and wave is different, depending on the wave direction.
Therefore the maximum values occur in waves of different periods.

In this example only the motion of the windward bilge and forefoot are included. A complete study must also contain the leeward bilge and the sole piece of the sternframe. When regular waves are used to predict the behaviour in confused seas it has to be assumed that the ship motions are linear with the wave height for an otherwise similar wave condition. This assumption has been adopted as a first approximation.

Response in irregular waves

When the wave spectrum and the response in regular waves are known the motion spectrum can be determined by means of the usual method in which the wave spectral density is multiplied with the square of the response operator. This has been done here for the spectra of Figure 14 and the response operators of Figures 18 and 19. Figure 20 presents the results for the vertical motion of the bilge in irregular beam seas. This motion has been made non-dimensional by dividing through the significant wave height. This quotient γ increases with increasing wave height which means that the relation between bilge motion and significant wave height is non-linear when, for instance, the wave height doubles from 2 m to 4 m the bilge motion becomes more than threefold in going from 0.68 m to 2.28 m. This phenomenon is caused by the fact that the ship motions are primarily influenced by the low frequency components of the sea, while Figure 14 shows that with increasing wave height this low frequency part of the spectrum grows more than proportionally.

FIGURE 21

- Figure -

Figure 21 gives the value of γ for the *forefoot motion* in head and following waves. The general character is very similar to the curve for the bilge motion in the previous Figure. The most striking difference is the much lower value of the forefoot motion, especially in following seas.

It must be kept in mind that the Figures 20 and 21 are not generally applicable but exclusively tied to the ship and wave conditions considered here.
In the present case it *appears* that the *danger* of bottom contacts is larger in the beam sea than in the other two wave conditions. The small forefoot motion in following seas compared to head seas may be of importance for some harbours where large tankers arrive (mostly following seas) in the deep draught condition and leave (mostly head seas) in ballast.

The necessary overdepth

For a given value of the significant wave height H the difference between the momentary deviation of the sea level and the average follows a gaussian probability distribution. Because the response of the ship in regular waves is assumed to be linear, the momentary vertical displacement of the critical points on the hull also follows a gaussian distribution. From the theory of *narrow spectra* it is known that the significant wave height is equal to four times the standard deviation of the gaussian distribution. Likewise the significant value of the ship motion is also four times its standard deviation. Therefore the probability distribution of the motion of the critical points on the hull can be derived from the significant wave height H and the value of γ. By means of the known gaussian function the percentage of time can be determined during which the critical points on the hull will be lower than β times the standard deviation $\frac{1}{4}\gamma H$.
Thus the overdepth $\frac{1}{2}H_S$ *necessary for* a certain wave condition can be determined with:

$$\tfrac{1}{2}H_S = \tfrac{1}{4}\beta\gamma H.$$

For the *sake of* simplicity this has been written as: $\frac{1}{2}H_S = \frac{1}{2}\bar{\alpha}H$ and therefore $\bar{\alpha} = \frac{1}{2}\beta.\gamma$ It has to be noticed that the value for γ, and therefore also the value of $\bar{\alpha}$, is a function of the wave height. This is contrary to the assumption used previously in this report where $\bar{\alpha}$ was taken as constant for a given wave direction. Further study is necessary in order to overcome this difficulty. It is not impossible that for the ship used here it would have been better to assume that the motions are proportional to the wave height squared. On the other hand, it is expected that for smaller ships γ will be less dependend on wave height. In order to illustrate this method an example is given here for the case where the tanker is steaming in beam seas with a significant height H = 5 m.

According to Figure 20 for this wave height $\gamma = 0{,}70$.
Suppose a *probability of bottom contacts* is required, such that during less than 0,001% of time the available overdepth is insufficient.

According to the normal distribution function in that case the overdepth has to be more than 4,27 times the standard deviation, so here $\beta = 4.27$. With the values of β , γ and H now available the *minimum* overdepth for beam seas can be established with the above given equation as $\frac{1}{2} H_S = 3.74$ m, which means that $\tilde{\alpha} = 1.50$.

Example

By means of the methods described in this report the depth of a harbour approach can now be determined. As an example this will be done here for the 100,000 ton tanker entering a harbour.
The tanker has a draught of 15.24 m and it does enter the harbour at a speed of 8 knots. It has been shown that the beam sea is the critical wave direction.
A preliminary survey indicated that the final estimate for the required waterdepth would be near to 1,2 times the ships draught. In that case Figure 11 indicates a squat of 0.40 m at a speed of 8 knots. From the model and wave study the value of $\tilde{\alpha} = 1.50$ has been selected. When it is considered that only during 1%, or less, of the time ships can be held up outside the harbour entrance the right half of Figure 17 indicates that ζ is about - 2.40 m for $\tilde{\alpha} = 1.5$. Therefore the bottom of the harbour entrance has to be at least $t + Z + \zeta = 15.24 + 0.40 + 2.40$ equals about 18.00 m below the mean sea level.

It is clear that the probabilistic method used here is not yet completely straight forward in all respects. Further studies will be made to eliminate the undetermined uncertainties which are still involved.
These studies will include the analysis of wave spectra and the determination of response coefficients in coastal areas and measurements on other models in waves.

4.4. Motions of vessels when approaching or vacating off-shore berths, situated in limited waterdepths and vessel's behaviour when moored to these off-shore structures

4.4.1. General considerations on off-shore berths

In some cases technical and economical considerations may exclude the possibility of dredging deep harbour approaches and building of alongside jetties within harbour basins, suitable to accommodate large vessels, crude oil tankers in particular. Off-shore berths, sometimes located in the open sea, would replace these protected harbours, provided, these berths allow the safe berthing and subsequent loading/discharging of these large vessels.

There are three types of off-shore berths viz: alongside jetties multi-buoy moorings and mono-buoy moorings.
These three types of berths are to be located as close as possible to the shore as to restrict the length of the submerged oil pipe line or pipe trestle from the berth to the coast. This immediately, brings into the picture the minimum depth requirement at the berthing site. It is noted that the submarine pipeline costs form the major part in the total costs of an off-shore single buoy berth.
The minimum depth required for these off-shore berths are of course related to vessel's motion. As for the multi-buoy mooring and the

alongside jetty berths, the vessel's motions have only little effect on these depth requirements, since moderate wind and sea conditions are the limiting factor to berthing operations and also to remaining at the berth, the motions of these large vessels are hardly noticeable at these types of berths. On the other hand the motions of the vessel when approaching a Single Point Mooring or when berthed to this type of mooring facility have a much greater influence on depth requirements, as this type of berth may still be operational under relatively rough sea conditions.
Of the three types of off-shore berths, alongside jetty type, multi-buoy mooring and Single Point Mooring (S.P.M.) in this paper attention will be concentrated on the latter as for this type ship's motions are of greater influence on depth requirements than for the other two. The following details regarding the berthing operations for each of these berths may be explanatory for the greater scope of the S.P.M. facility when compared with the others. The use of an alongside jetty built in the open sea or bay may in some cases have preference to a buoy berth, assuming that wind and sea conditions allow the vessel to be berthed and to remain at the berth during a number of days per year sufficient to make this off-shore terminal operationally and economically attractive.
Although an off-shore alongside jetty may be provided with the appropriate fendering system, any significant deviation of the approach speed of the vessel, greater than for which the jetty and fendering has been designed, may be desastrous for the whole structure.
Tug assistance will be required in many cases to keep the large vessels under control. When during the berthing operation sudden wind squalls are experienced with speeds of, say 25-30 mph, it may still be very difficult to manoeuvre the vessel into the berth, particularly when the wind direction is already slightly abeam of the ship.

When the vessel is moored to the alongside berth, whilst wind and wave conditions deteriorate, the mooring cables, which provide a relatively stiff connection with the jetty, may break as a result of a combination of vessel's motions and constant wind forces. The vessel may finally break adrift, endangering herself and the jetty structure.

As for this type of berth both vessel and structure are at stake, it is safe practice that berthing operations are delayed and vessels are ordered to leave the berth when conditions are still relatively moderate.

A suitable berth to accommodate large vessels at off-shore sites at which moderate wind and sea conditions prevail, is the multi-buoy mooring. The vessel is moored to a number of buoys and also to her own cables and anchors.
As for the multi-buoy mooring the risks involved are not so great since for this type of berth slight damage to the vessel may be the result of a malperformed manoeuvre at which one or two mooring buoys may be touched. Although for this fixed heading mooring, it may also be difficult or even impossible to manoeuvre the vessel into the berth at beam winds. The berthing operation is quite cumbersome, first of all the vessel drops her bow or port anchor, sails slowly ahead and

- drops -

drops her second anchor, swings back with her stern towards a series of mooring buoys. Other mooring procedures might be adheared to depending on conditions connected with the site.
One, in many cases two mooring launches assist in making the cable connections between the vessel and the buoys, of which sometimes a number of five are necessary to keep the vessel safely in the berth. For some of these multi-buoy moorings tug assistance is also required to facilitate the mooring operations.
This fixed heading multi-buoy mooring will usually be orientated with its longitudinal axis parallel to the prevailing wind/wave direction. In some cases a strong current with a direction different from the prevailing wind direction is determinant for the direction of the berth. As for the alongside berth, the vessel has to vacate the berth when wind and sea conditions deteriorate, particularly in case of beam winds, generating waves which cause the vessel to roll to such a degree that loading or discharge operations need to be stopped. At the same time the loads in the mooring cables may become too high owing to great wind loads and considerable motion of the vessel.
It is noted that the magnitude of these loads as a result of ship's motion depends on direction of wave approach and wave characteristics e.g. swell conditions may initiate resonance of the spring system of the vessel and mooring cables. (Reference is made to an article on model experiments on the mooring of large tankers [6].)
It is concluded that previous to the need to consider depth requirements, the berth will have to be vacated already when motions of the vessel are still relatively small.
Depth requirements were therefore up till now already fullfilled when allowing for a few feet under keel clearance. For a specific site, however, a more thorough study will need to be made as the size of the vessels now available may require a greater average under keel clearance, than being considered so far. This study should include the assessment of the max. conditions at which berthing of the vessel can still be effected and also of the wind and sea conditions at which the berth need to be vacated. General information on ship's movements at certain conditions can be obtained from a report issued by U.S. Naval Civil Engineering Laboratory California.[7]
The third type off-shore berth developed to moor large vessels and allowing the discharge or loading of crude oil and oil products is the Single Point Mooring (S.P.M.) or mono-mooring. The vessel is moored at the bow to a single fixed structure or to a single buoy, and is free to swing around this centre point, following the direction of the resultant of wind, current and wave forces acting on the tanker. The latter berth is intended to be operable under wind and sea conditions more severe than for the off-shore berths mentioned herefore.

The mooring of a vessel to an S.P.M. is relatively simple. The vessel is approaching the Single Point Mooring, in a direction more or less parallel to the resultant of wind and current forces. When the vessel is a few hundred feet away a messenger line is passed over the fair leads at the bow of the ship to a small though seaworthy

mooring launch. The crew of this launch connects this line to the end of the mooring cable, attached to the S.P.M., either a fixed structure or a single buoy. (Single Buoy Mooring). Normally two mooring cables are provided. These cables are hove in and attached to the bollards at the forecastle deck of the vessel.The actual mooring up can be done within half an hour.
Greater effort is to be applied to attach the hoses for discharge/ loading oil to the ship's manifold. Launch attendance to assist in making the S.P.M. mooring cable connections and also the hose connections implies that the mooring of the vessel can-not be effected under conditions at which the launch crew is unable to work. These conditions are, however, more severe than those limiting multi-buoy mooring berthing operations. This has been clearly demonstrated at an off-shore loading terminal in Sarawak - North Borneo, where at Lutong/Miri, both multi-buoy moorings and a Single Buoy Mooring were in operation simultaneously in the South China Sea during a few years. Consequently the remaining multi-buoy moorings are now all being replaced by Single Buoy Moorings.
Remaining at the berth is for an S.P.M.berth permissible under much rougher conditions, as the vessel is seeking a direction at which resistance to wind, current and waves is at a minimum. Loads in the mooring cables are still within limits of the safe working load of these cables under severe conditions, say up to wind force Beaufort 7 to 8.

4.4.2. Description of mono-mooring berths

Two types of mono-mooring or Single Point Mooring are now in operation.

a) The mono-fixed structure tanker berth. The centre point is a piled structure to which the tanker is moored by two mooring lines. The oil flows through a submarine pipeline, a riser pipe attached to the structure, and a long semi-submerged boom to the midships manifold of the vessel.
Both this boom and the vessel can swing around the fixed centre point. This type of berth, of which only one has been built, is now being used at Marsa Brega, Libya, by ESSO [8].

b) The mono-buoy mooring or Single Buoy Mooring, (S.B.M.). The centre point is a relatively small buoy anchored to the sea bed by means of chain cables.
The oil connection between mid ship's manifold and buoy consists of floating hoses.

New in the conception of the single buoy mooring is the oil connection and the oil swivel arrangement on the buoy, which allows the vessel to swing freely around the buoy whilst the oil is being pumped through. Further details on the Single Buoy Mooring can be found in [9]. The first Shell SBM suitable for oil tankers, operational since early 1961 in the South China Sea, North Borneo, was built after the principle of the system had been tested and also compared with a multi-buoy mooring in the Ship's Model Basin at Wageningen on behalf

of the Royal Dutch/Shell Group in 1957 and 1958. [6]
The SBM system consists of the following items: (Fig.22, 23, 24)

1) Buoy,
2) Chain cables/anchoring system
3) Submarine hoses
4) Floating hoses
5) Mooring cables.

Details of the SBM buoy will follow the description of the other SBM parts.

Chain cables

The buoy is moored to the sea bed by chain cables attached at their ends to heavy anchors or anchor piles. Figure 22 shows a layout with eight chain cables. Other mooring layout configurations would be possible depending on conditions connected with the location.

FIGURE 22

Underwater hoses

The oil stream flowing through the SBM system leaves the submarine pipeline and enters the underwater hoses which are located between the buoy and the submarine pipeline. Hoses with a size of 16" (40 cm) I.D. are now in use and larger sizes are being considered.

Floating hoses

The oil passes via the buoy into the floating hoses, which are located between the buoy and the tanker and are connected to the midships manifold. (Fig.24)
Foam plastic rings provide the flotation for these hoses. The largest size of floating hose now in use is 12" (30 cm) I.D. In one case three strings are tied together by means of conveyor belt-type connectors. Also for the floating hoses the use of 16" I.D. size or larger is now being considered.

Mooring cables

The mooring loads exerted by the vessel are transmitted to the buoy by means of two cables, mainly consisting of nylon ropes provided at both ends with short lengths of chain cable or wire rope. The nylon ropes act as shock absorbers.

Buoy (Figures 23 and 24)

The outside diameter of the cylinder is some 27'-30' (some 8 to 9 m) and the diameter of the inner cylinder is some 10' (3 m). The underwater hoses are lifted through this cylinder and attached to a central pipe assembly.
The swivel or a combination of more than one swivel can freely rotate around this centre pipe assembly together with the top platform, to

which the two mooring cables are attached. This platform transmits the mooring loads to the buoy body through a number of wheel bogies running on two large diameter circular rails. The skirt at the bottom of the buoy body supports the ball stoppers which enclose the chain cable links and provides also a protection for the floating hoses if the vessel touches the buoy. During mooring operations, it happens that the vessel overrides the buoy, thereby touching the fendering of this bottom skirt.

There is no doubt that the motions of the vessel when moored to an S.P.M. certainly affect the depth requirements at the berthing site. During the first full scale test under rough conditions with a 33,000 dwt ton tanker moored to a Single Buoy Mooring in the Japanese Sea, apart from measuring the loads in the mooring cables, it was also attempted to measure pitch, roll and heave with very simple means though.

4.4.3. Ship's motions. Off-shore S.B.M. berth in the Japanese Sea

During winter 1961/1962 an S.B.M., laid in the Japanese Sea, in water depth of 20 m, 1.9 nautical miles off-shore was tested under severe conditions as a berth suitable for large tankers.

It was investigated (a) what limitations were imposed by the use of mooring launches and mooring the vessel, (b) what loads could occur in the mooring cables and (c) also what the ship's behaviour would be considering the severe winter conditions prevailing at Niigate.

With respect to the vessel's behaviour, the basic idea was to establish the relationship between certain wind/sea conditions and the subsequent behaviour of the vessel moored to the S.B.M. buoy. This would enable to assess the depth requirements at the berth location, thereby also taking into account the above points (a) and (b). For this relationship it would be necessary to obtain information wave observations at the selected site, and of course, records of the vessel's motion, when approaching the mooring and when berthed to the S.B.M. Regarding the wave observations off the Niigata coast little information was available at that time. Japanese Harbour Authorities were collecting wave observations to a limited extent in shallow waterdepth only.
As wave recorders could not be made available in time, wave instrument records could not be obtained during the testing period.
However, visual observations were made. A Froude beacon, placed as close as possible to the S.B.M. site was used as an aid in assessing the wave heights.
The motions of the vessel, pitch, roll and heave were observed. It is noted that these observations have also limited accuracy. From pitch and roll records draught increase at forward/aft and at port/starboard were computed, taking into account the length and width of the vessel. The results thus obtained are shown in Fig.25 A, B and C. As can be seen on these graphs the plotted points are quite scattered. A line of maximum values has been drawn therefore as to arrive at a curve from which max. draught increase figures can be predicted for various conditions.

The maximum draught of the vessel when fully loaded was 34'4" (with slightly uneven keel). The depth requirements therefore for this 33,000 dwt ton tanker would be: 34'4" + 14'6" = 48'10", say 49' when approaching the berth at almost zero speed at 6 ft average wave conditions. Owing to launch assistance it can be observed that this wave height is to be considered as a limiting condition for mooring operations. It is assumed that for manoeuvring the vessel into the berth an approach circle with a radius of some 3 times the ship's length would be necessary.
This would involve that at the periphery of the circle a depth of 49' would be sufficient. (Tidal differences are negligible at Niigata, the influence of squat at the low speed at which the vessel enters the manoeuvring area is also very little, refer separate section on squat). Considering the vessel when moored to the S.B.M., the depth requirement would be 34' 4" + some 19 ft totals some 54 ft when 10 ft average waves are experienced (refer Fig.25 C). This wave height may for instance be considered as the limiting condition for a vessel remaining safely at the S.B.M. berth. This depth of 54 ft would be required at a distance from the S.B.M. buoy of say 1.5 times the length of the vessel.

4.4.4. Further investigations on ship's motions

For the planning and the design of future off-shore berths it was thought necessary to obtain more detailed and accurate information on the ship's behaviour when approaching or being moored to an S.B.M. This becomes particularly apparant when an SBM berth is to be designed for conditions at which the directions of both the current of say more than 0.5 knot and the prevailing swell/waves differ appreciably, say more than 30°.

Tests were conducted in the Ship's Model Basin to investigate this phenomenon. As these tests were carried out in the deep water tank, the depth requirements which may be derived from the results obtained can be considered as the asymptotic conditions of the shallow water case. Due to the non-linearity of both the mooring system of the buoy and the connection between buoy and ship, the transfer function $\tilde{\alpha}$ becomes also a not linear function of the waterdepth.
Due to this fact formulae 4.1 has to be replaced by
$\zeta = A + W - \frac{1}{2} f(W) \alpha' H$

where α' is also a non-linear function of H. Formulae 4.2 is applicable, providing $P(H_k)$ is weighed with $f(W)$.

A further series of tests will be carried out to investigate the behaviour of tankers up to 120,000 dwt ton class and to establish the mooring loads for such vessels moored to an SBM in limited waterdepth.

The results of these tests will be produced at the Stockholm conference.

Summary.

The position of the vessel with respect to the sea bed is determined by three factors namely:

a) the height of the water level undisturbed by waves (astronomical tides plus wind effect);
b) the position of the deepest point of the moving vessel on restricted water (draught plus squat);
c) the movement of the extreme points of the vessel's hull as imposed by the water movement due to waves (roll, pitch and heave).

The factors mentioned under a and c have a statistical character as they are closely related to meteorological conditions. The wind effect, being the difference between the predictable astronomical tide and the actual sea level shows a nearly normal (gaussian) distribution in each selected group of wind force and direction. Relative to this waterlevel, undisturbed by waves, allowance must be made for squat, which is the decrease in the clearance under a ship's keel caused both by bodily sinkage and by change of trim. Model tests, confirmed by field observations, have made it possible to estimate this decrease of under keel clearance in fairways of various shapes.

If the water surface is disturbed by waves the vessel is moving under the influence of these waves (roll, pitch, heave) the amplitude of the extreme points of the vessel is influenced by the wave spectrum, which can be characterised by its significant wave height. The probability of occurrence of the significant wave height can be determined in the selected groups of wind force and direction, using the same statistical approach as for the wind effects. The probability distribution of the motion of the critical points of the hull can be derived from the significant wave height and the ship's response coefficient.

The response coefficient must be determined with model experiments in shallow water. Distinction has to be made between two cases viz: the free moving vessel and the vessel moored at an off-shore berth.

When during the model tests regular waves are used to predict the behaviour in confused seas it has to be assumed that the ships motions are lineair with the wave height for an otherwise similar wave condition. This assumption has been adopted as a first approximation. When for this case the wave spectrum and the response in regular waves is known the motion spectrum can be determined by means of the usual method in which the spectral density is multiplied with the square of the response operator.

Of the three types of off-shore berths, alongside jetting type, multi-buoy mooring and single point mooring in this paper attention will be concentrated on the latter as for this type ships motions are of greater influence on depth requirements than for the other two. The single point berth can be used under more severe wind and sea conditions.

- Due -

Due to the non linearity of both the mooring system of the buoy and the connection between buoy and ship the response function becomes also a not linear function of the water depth and wave height.
This calls for special precautions when determining the probability distribution of the ships motion.
By introducing statistical considerations as mentioned above for each possible depth of the fairway or berthing site a chance can be determined when it will be not safe for tankers of a certain size to make use of it. When comparing the losses due to these delays with the extra costs required for obtaining a greater depth, a decision can be made about the design criterion.

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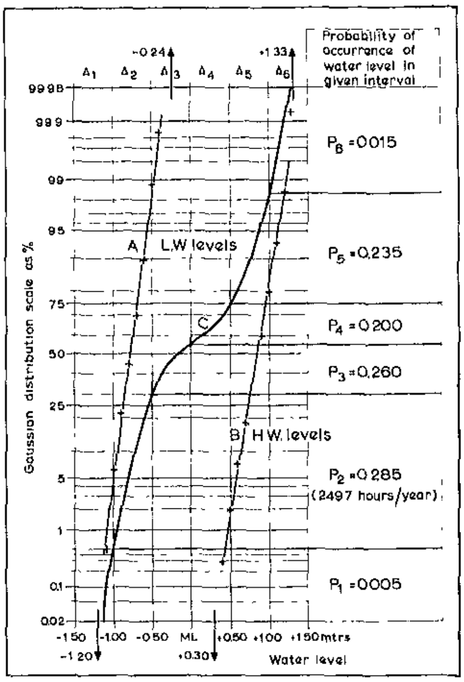


Fig.1 ASTRONOMICAL TIDE AS STATISTICAL PHENOMENON

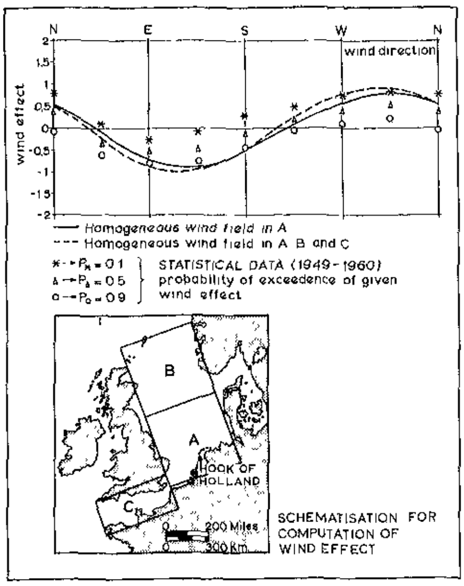


Fig 2 EQUILIBRIUM WIND EFFECT AT HOOK OF HOLLAND COMPUTED FOR WIND FORCE 7 BEAUFORT

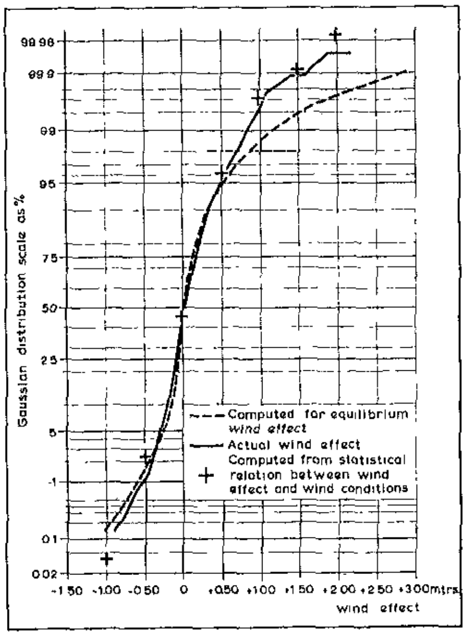


Fig.3 STATISTICAL DATA ON WIND EFFECT AT HOOK OF HOLLAND (1949-1960)

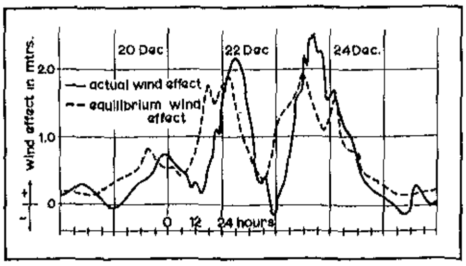


Fig 4 ACTUAL AND COMPUTED WIND EFFECT DURING GALE IN 1954 (AFTER WEENINK 1956)

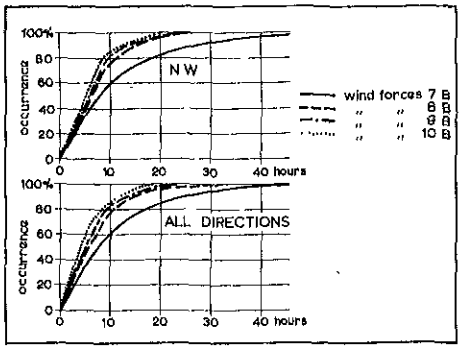
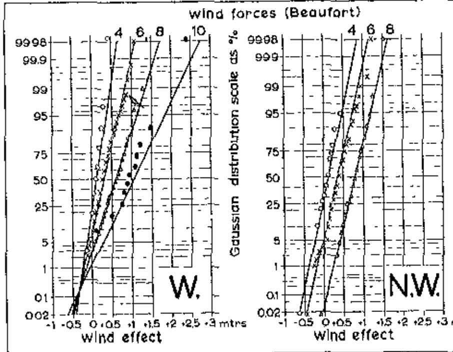


Fig. 5 DURATION OF WIND IN NORTH SEA AREA FOR DIFFERENT WIND FORCES



Number of observations

B	W	NW
4	34	19
6	356	172
8	84	53
10	11	—

Fig. 6 CUMULATIVE PROBABILITY DISTRIBUTION OF WIND EFFECTS CAUSED BY W AND N.W WINDS AT HOOK OF HOLLAND

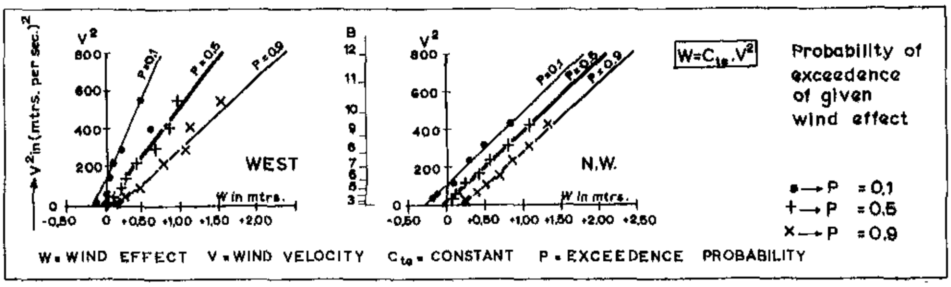


Fig. 7 RELATION BETWEEN WIND EFFECT AND WIND VELOCITY

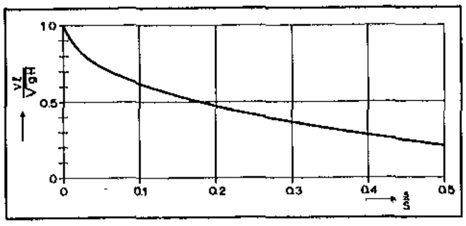


Fig. 8 SCHIJF LIMITING VELOCITY = $V\ell$

P = Depth , t = Drought

$Z_{max.}$ = Maximum squat

S = Cross sectional area

s = Midship area

E = Width at water surface

B = Beam amidships

$L = \frac{S}{P}$ = Mean width

$H = \frac{S}{E}$ = Mean depth

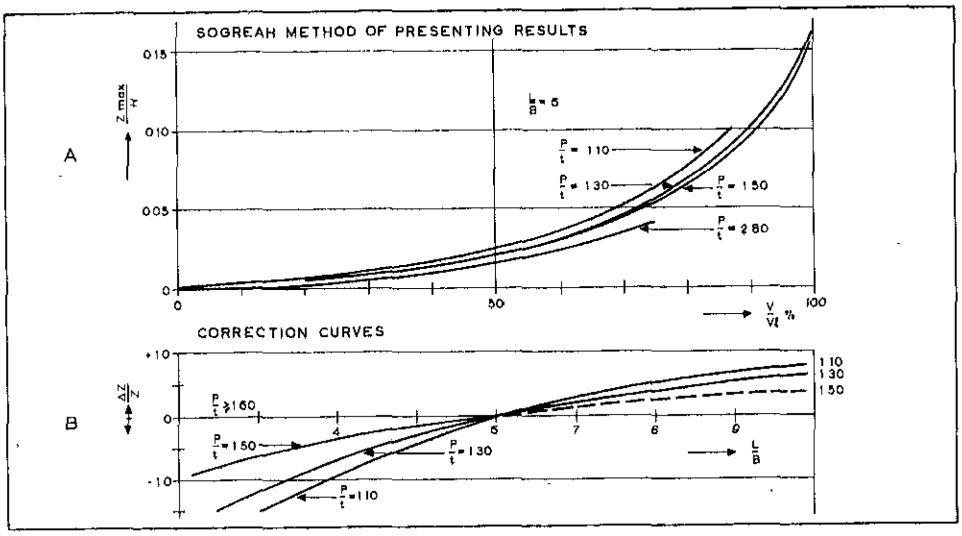


Fig. 9 MAXIMUM SQUAT

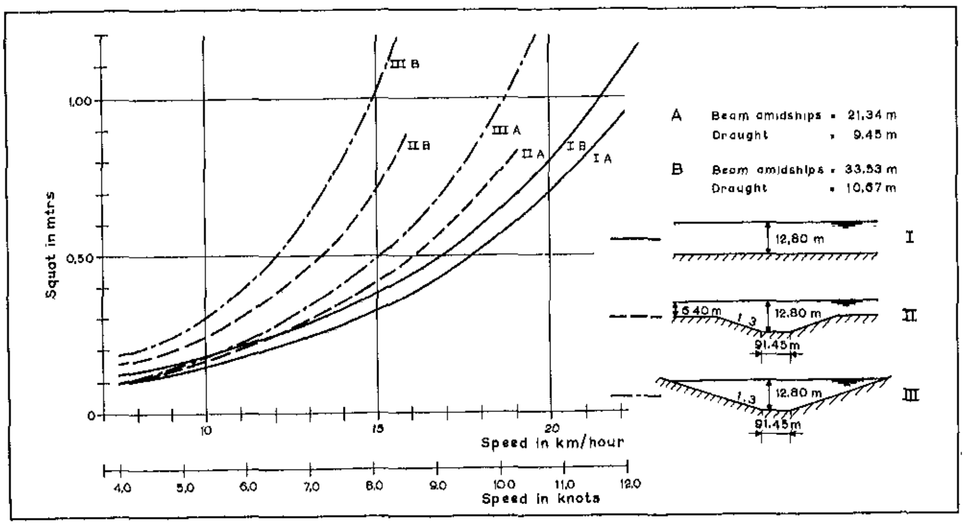


Fig.10 SQUAT CALQULATED BY SOGREAH METHOD

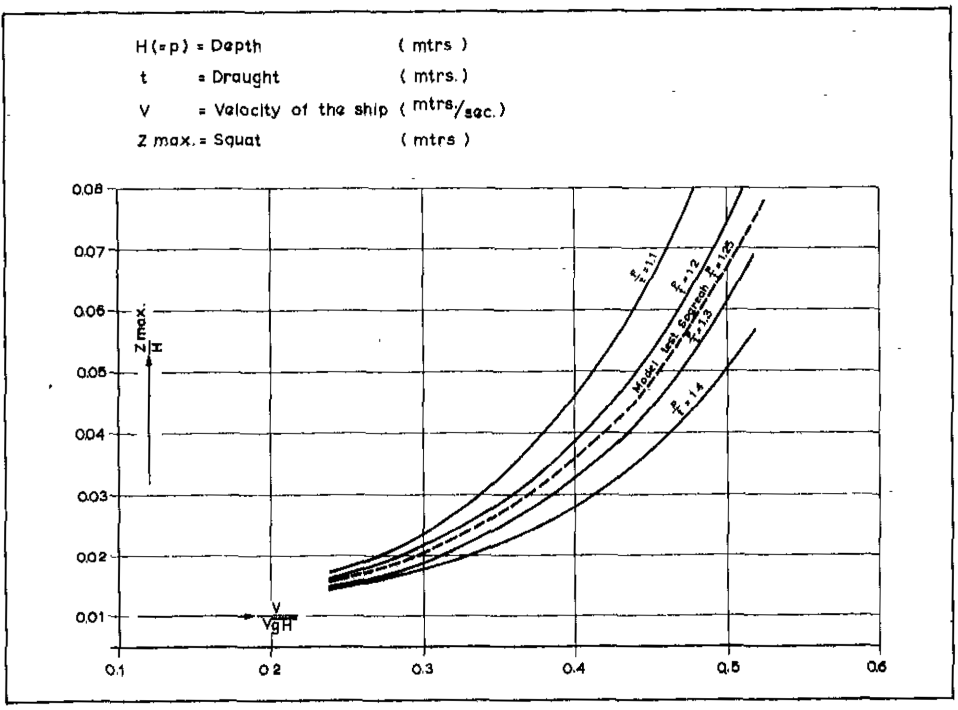


Fig. 11 MAXIMUM SQUAT MODEL TESTS N.S.P.

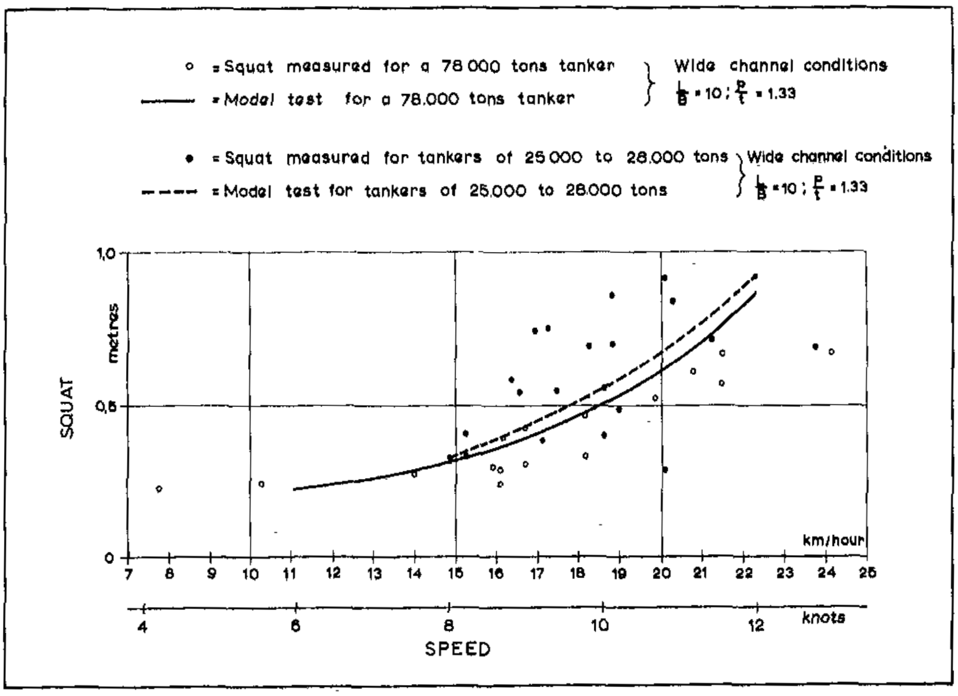


Fig. 12 SQUAT MEASUREMENTS IN NATURE

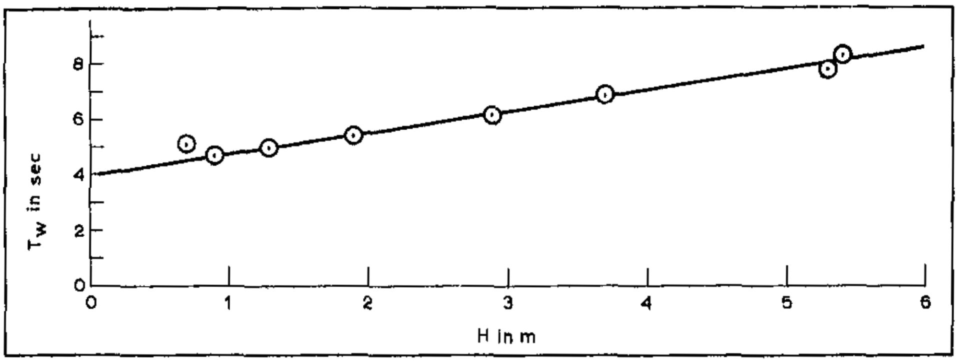


Fig. 13 RELATION BETWEEN AVERAGE OBSERVED WAVE HEIGHT AND PERIOD ON THE NORTH SEA

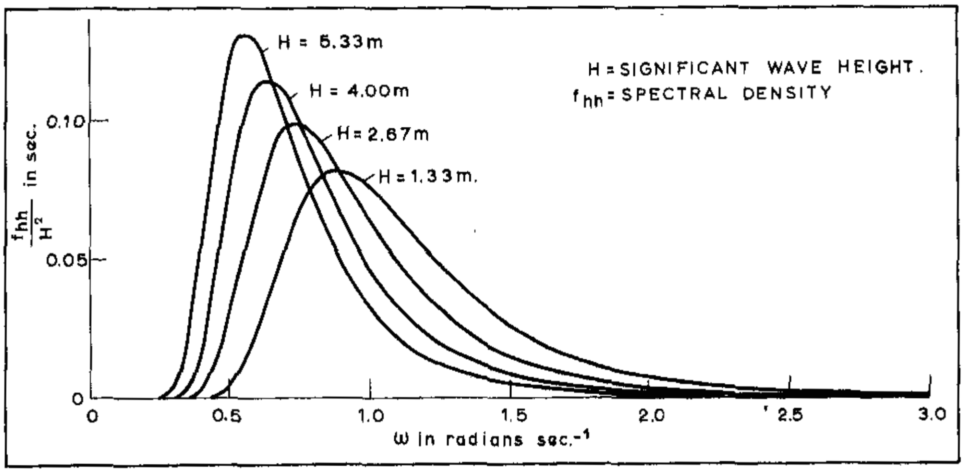


Fig. 14 WAVE SPECTRA USED FOR FIGURE 20 AND 21

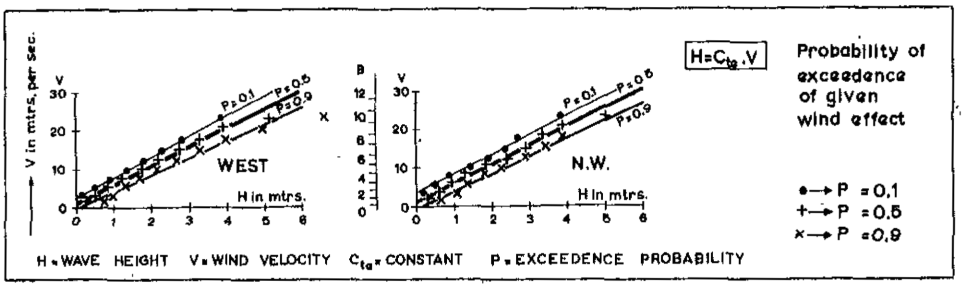
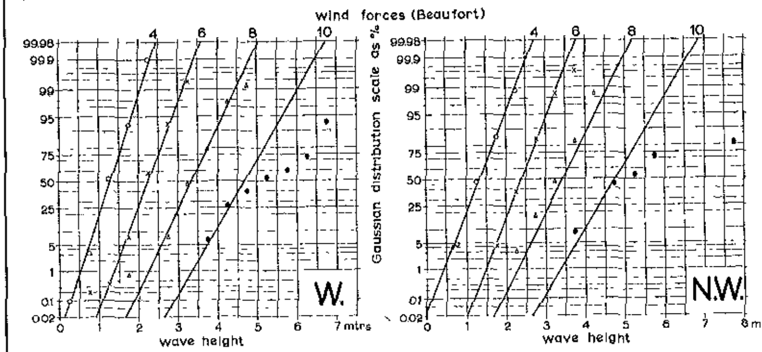


Fig. 15 RELATION BETWEEN SIGNIFICANT WAVE HEIGHTS AND WIND VELOCITIES.



Number of observations

B	W	NW
4	1079	567
6	518	268
8	130	64
10	16	11

Fig.16 CUMULATIVE PROBABILITY DISTRIBUTION OF WAVE HEIGHTS CAUSED BY W. AND NW. WINDS

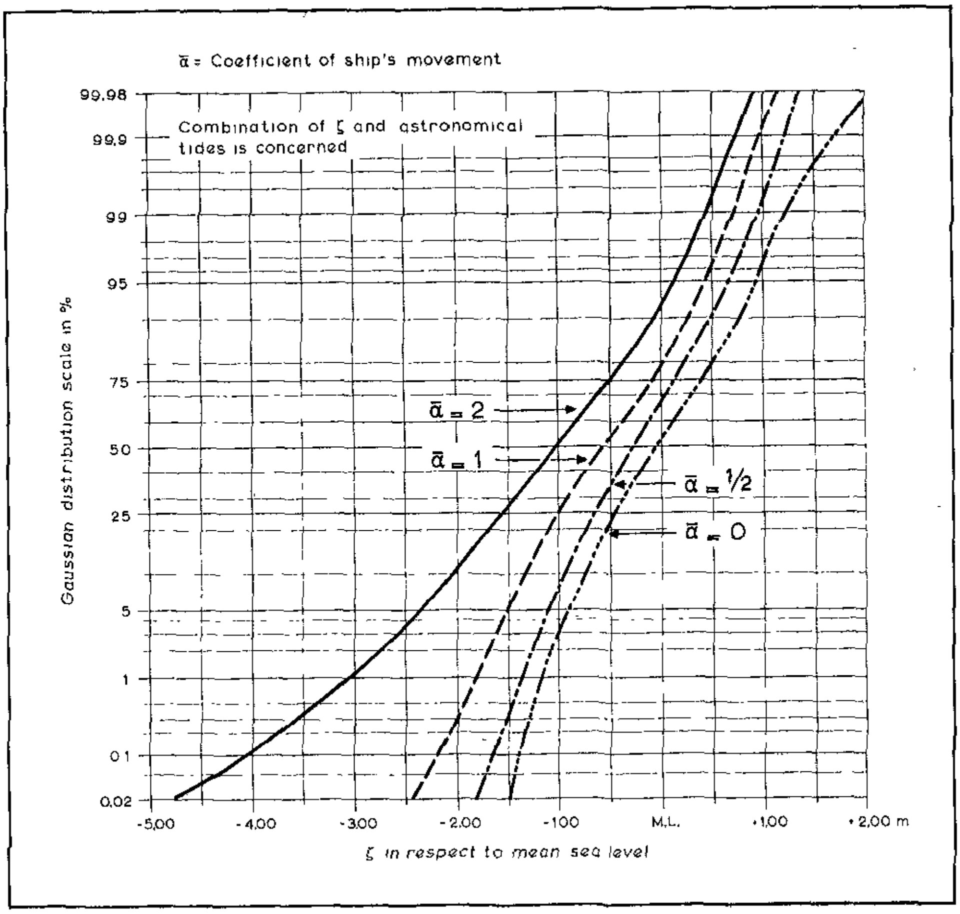


Fig.17 RESULTING CUMULATIVE PROBABILITY DISTRIBUTIONS OF THE LOWEST POSITION ζ OF SHIP'S KEEL

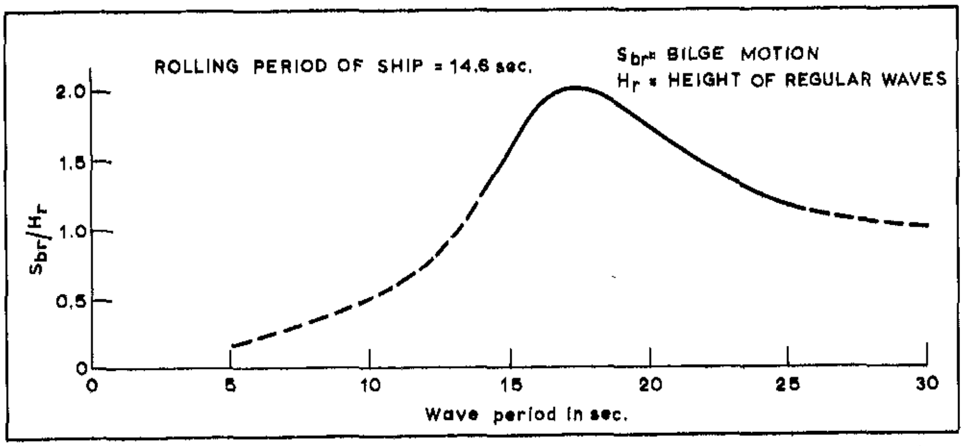


Fig. 18 RELATION BETWEEN BILGE MOTION AND REGULAR WAVE HEIGHT IN BEAM SEAS

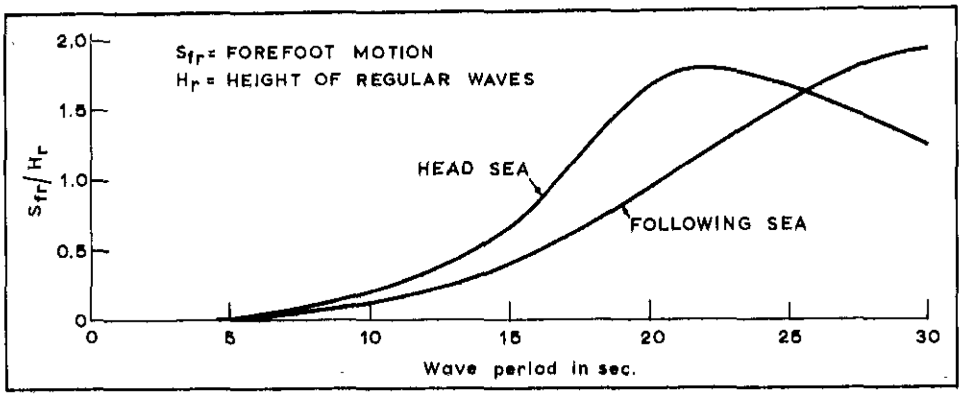


Fig. 19 RELATION BETWEEN BILGE MOTION AND REGULAR WAVE HEIGHT FOR A 100,000 TDW TANKER IN HEAD AND FOLLOWING SEAS

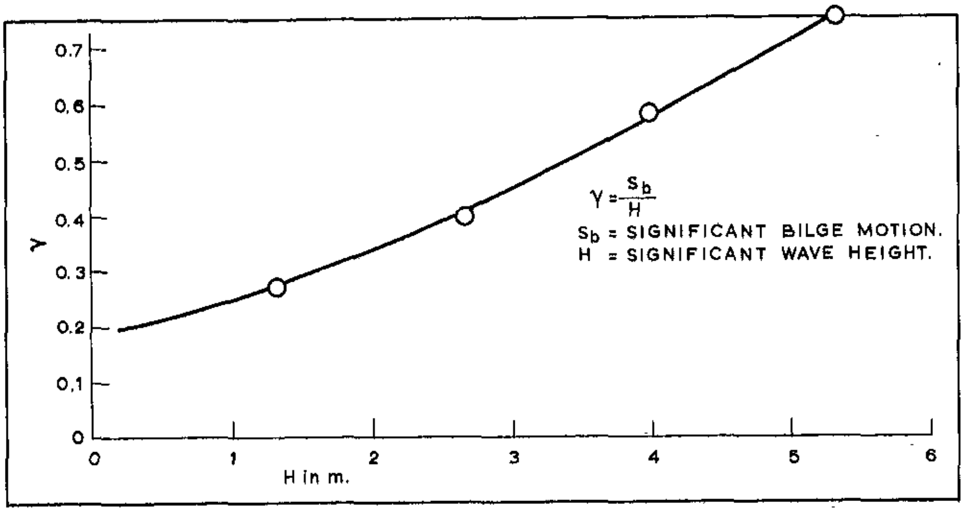


Fig. 20 RELATION BETWEEN WAVE HEIGHT AND BILGE MOTION IN LONG CRESTED BEAM SEAS.

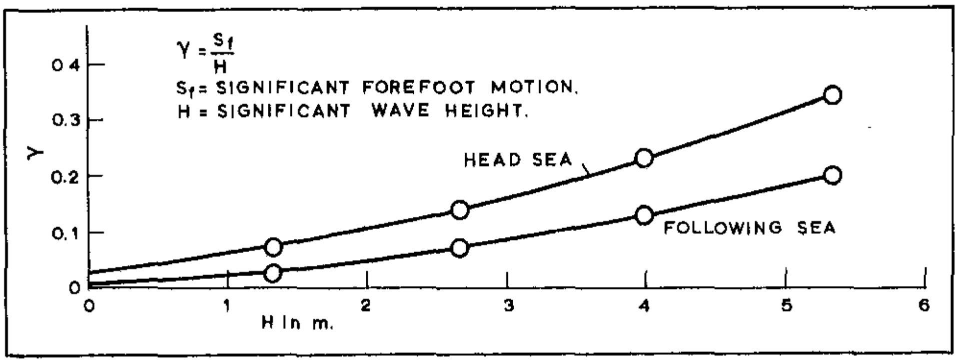


Fig. 21 RELATION BETWEEN WAVE HEIGHT AND FOREFOOT MOTION IN LONG CRESTED HEAD AND FOLLOWING SEAS

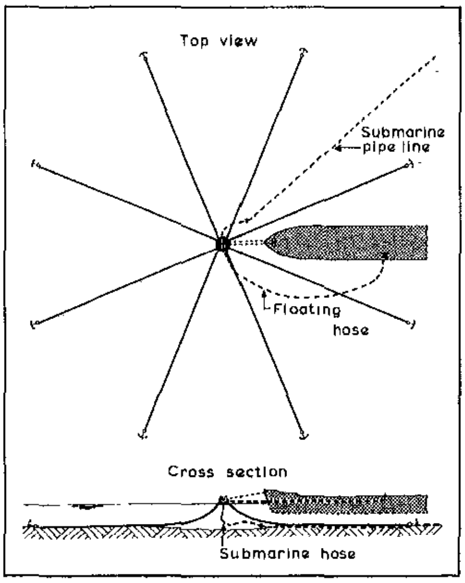


Fig 22 SINGLE BUOY MOORING.

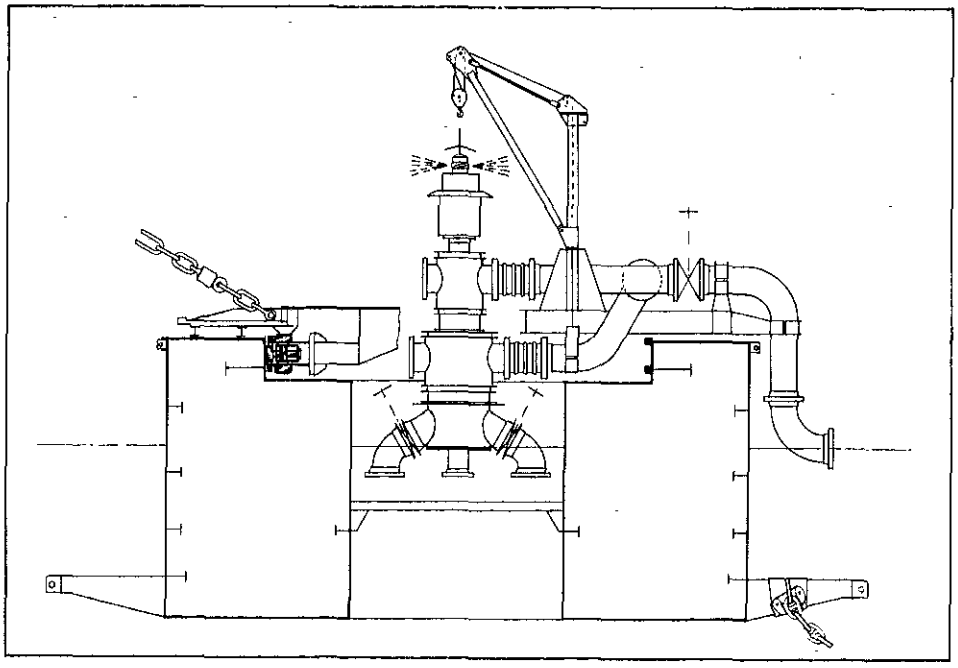


Fig. 23 SINGLE BUOY MOORING, CROSS SECTION

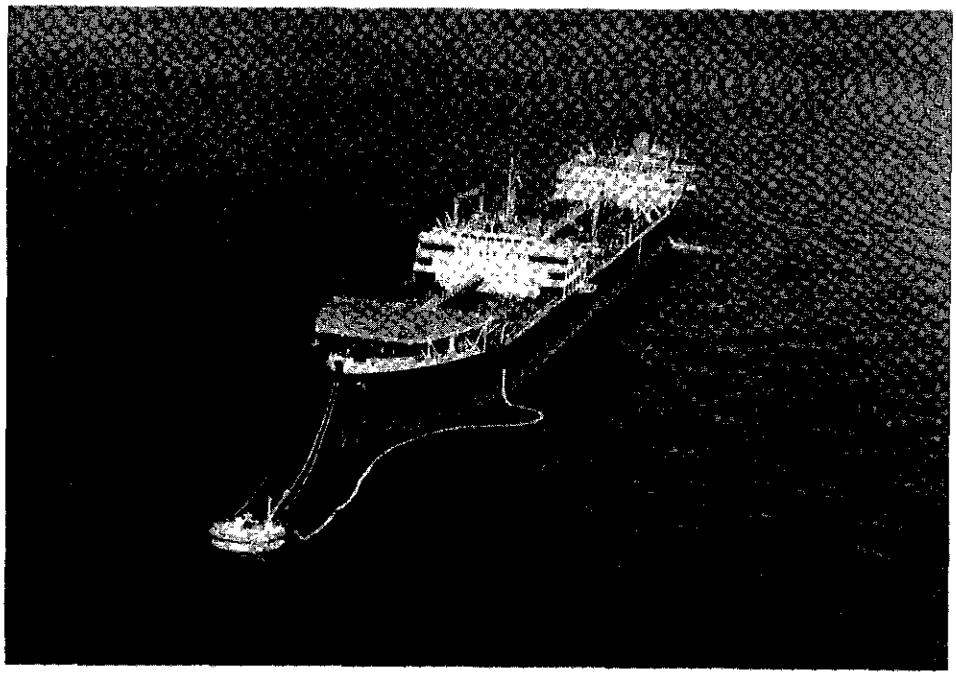


Fig 24 TANKER PERMANENTLY MOORED TO AN S.B.M. BUOY AS A STORAGE TANK, FLOATING IN THE OPEN SEA. IDD EL SHARGI, QATAR, PERSIAN GULF.

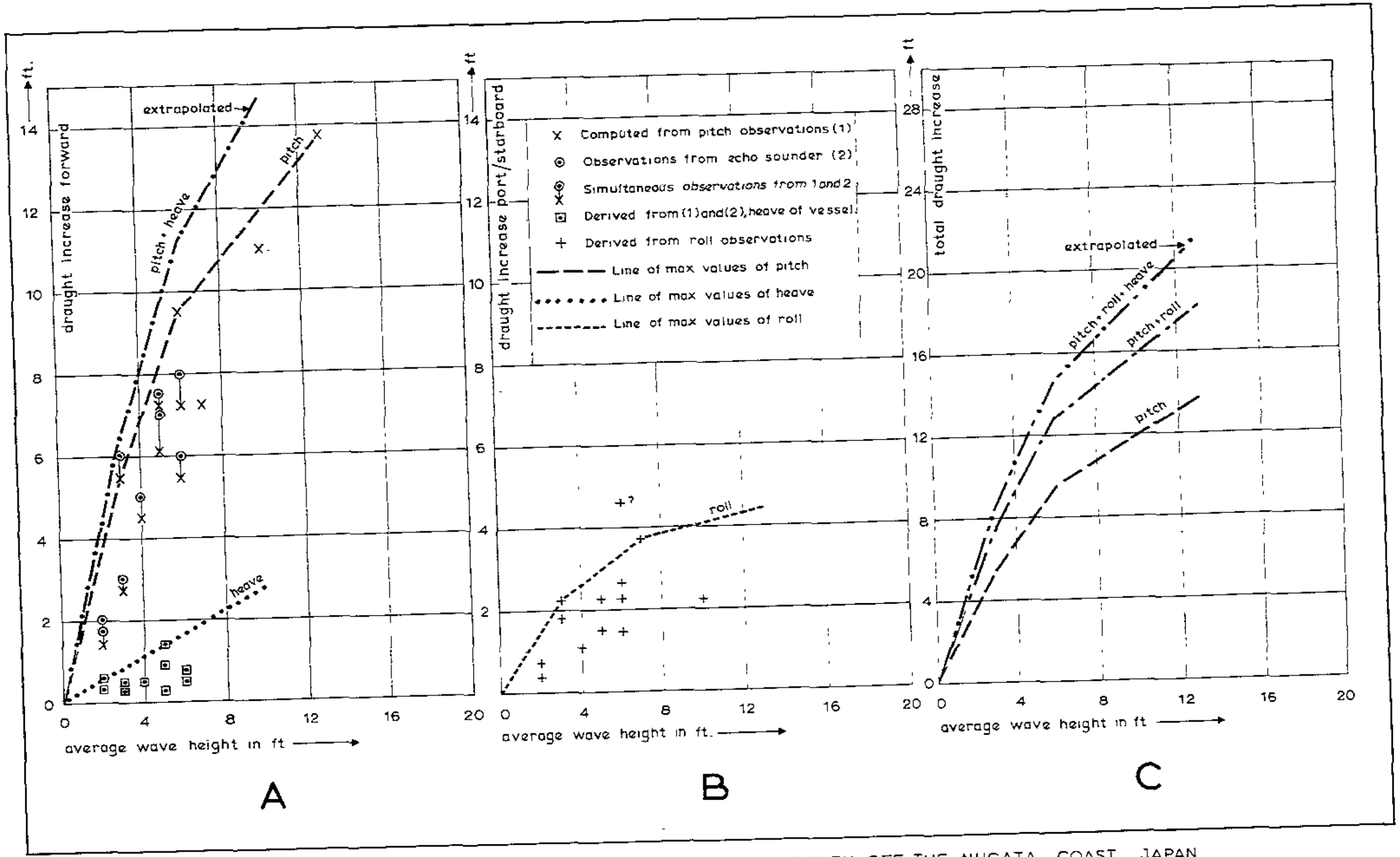


Fig 25 DRAUGHT INCREASE OF A 33,000 dwt TON TANKER MOORED AT S.B.M. BERTH OFF THE NIIGATA COAST, JAPAN