PAPER No. 9

SAFETY AT SEA

Stability of Ships, Safety from Capsize, and Remarks on Subdivision and Freeboard

by Walter Abicht*, Sigismund Kastner† and Kurt Wendel‡

SUMMARY: In spite of recent progress in describing ship roll motion behaviour from theory and experiments, in design practice a static balancing of uprighting and upsetting moments for assessing ship stability is advocated. Roll motion dynamics can be accounted for by comparing encounter wave spectra with a probabilistic distribution of natural roll frequency. Stern quartering seas appear to be the most dangerous.

Section 2 demonstrates how the effectiveness of tanker sub-division can be evaluated. An example shows the potentially great reduction in accidental oil pollution if tank sizes are limited according to the new IMCO rules for oil tankers. Furthermore, the comparative advantages of double skin and double bottom construction are shown.

Section 3 gives a physical explanation for the relative increase of basic freeboard against ship length.

1. STABILITY OF SHIPS AND SAFETY FROM CAPSIZE

by S. Kastner

Safety of a ship from capsize at any operating condition must be ensured from the design stage. The ship master must have guidelines on how to load and operate his ship safely. In operation the ship must be treated as a free floating body subject to motion excitation. Thus any ship in motion must be stable as well. The uncoupled motion equation of a ship for one degree of freedom may be written as

$$\ddot{\phi}(\phi,t) + N(\dot{\phi},t) + F(\phi,t) = K(\phi,t) \qquad (1)$$

It is obvious that equation (1) will be difficult to solve for all possible ship conditions and external exciting forces which might be expected to act on the body during its lifetime. For this reason the stability of motion is treated mainly by studying the different terms in this equation.

In an historical sequence, we see increasing effort and knowledge in treating stability parameters of the motion equation:

(i) First, only the restoring moment in the upright ship position was considered,

$$F(\phi) = g\Delta GM\phi \qquad (2)$$

(ii) After the capsize of the British warship CAPTAIN in 1870 it became evident that the dependence of the restoring moment on the heel angle also had to be considered. Unfortunately, naval architects stayed at this stage for decades, trying to conceive sufficient righting arms or sufficient area beneath the righting arm curve, respectively, for any kind of ship mainly by trial and error. During that era, the well-known work of Rahola(1) was published. He analysed the then known stability accidents for certain minimum required values of the righting arm, the main part of the term F in equation (1). His findings on the minimum required righting arm agreed quite well with other proposals made since the turn of the century. However, his sample size was not at all statistically significant, as was shown by Wendel(2) in 1965. But still, many of the national stability regulations or recommendations rely on the Rahola type approach, including the IMCO Recommendations(3) on ship stability adopted in 1968. Certainly, one reason for the continued application of this approach is the small calculation effort, since only the cross curves of static stability in still water need to be calculated. In some of the national regulations, the so-called weather criterion is used, which includes the influence of wind heeling on the area under the righting arm in still water.

There are serious objections to continuing to advocate any Rahola type approach. It can be shown in many cases that some amount of minimum required righting arm, say 20 cm at 30° heel, or some minimum area under the righting arm curve, does not guarantee a safe ship for all ship types. This is particularly true if the influence of the seaway must be taken into account. On the other hand, authorities still operating the Rahola approach rely mainly on their experience and update the ship sample size with later built and classified ships. But it is obvious, and all experts seem to agree, that for newly developed ship types where there is no experience and insufficient statistical information available, this method must fail.

So it is all the more surprising that in the new stability rules for semi-submersibles set up by the American Bureau of Shipping in 1973, the Rahola type approach has been retained.

(iii) Since the early 1950s, in order to overcome the deficiencies of the Rahola type stability approach, Wendel has proposed that uprighting and heeling moments should be balanced in a hydrostatic manner. His method takes care of different external conditions such as wind, heel due to turning, shifting loads and seaway. On the basis of this static balancing, stability regulations were developed which up to now have proved to be successful by setting stability standards for authorities, by influencing ship design and by

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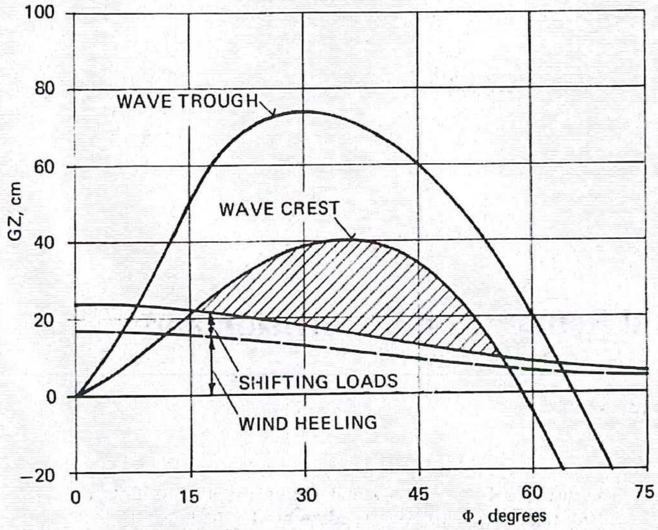


Fig. 1. Balancing of Righting Levers

preventing capsizes. A thorough description of the stability concept employed can be found in the 1965 Transactions of STG(4).

The main feature of the moment balancing is a static comparison of uprighting and heeling moments of the ship for certain defined conditions. All moments are to be divided by the displacement, i.e. uprighting and heeling levers are considered. This method keeps the advantage of simple static calculations for all moments to be included. That is true even for the influence of the seaway, which is taken into account by the calculation of the hydrostatic righting arm variation in a wave crest and wave trough in a longitudinal regular wave of ship length. Fig. 1 shows an example of moment balancing of a ship with shifting cargo, wind heeling and seaway righting arms.

Even with this method of moment balancing, where the moments met in reality are included, there still remains the problem of how to ascertain the right magnitude of the residual righting arm for safety from capsize. Still, roll motion dynamics are not yet specifically mentioned, but treated implicitly. The residual righting arms required after balancing are supposed to take care of all possible dynamic effects, which were not included in the static moment calculations.

The residual righting arms required for safety from capsize had been based on an evaluation of capsizing tests with free running ship models in following and stern quartering seas. With model tests, a larger sample of critical capsize conditions at defined ship parameters could be gathered. Furthermore, capsizing model tests allowed the motion behaviour at extreme roll amplitudes to be studied. Previously, this had been confined to speculation. From 1961 to 1969 five different hull forms were tested, first at Lake Plön(5), then at the Eckernfoerder Bucht. Natural wind generated waves were used for excitation, thus modelling natural random seaway conditions, and enabling a long test distance to be run in quartering seas as well. Since such random model tests with free running models are time consuming and expensive, a method for choosing significant test conditions was developed(6). It included the choice of combinations of ship parameters such as freeboard, metacentric height, speed, heading and seaway conditions, where dangerous roll motion may be expected, as well as a statistical test on the sample size.

A sophisticated test programme with free running ship models has been carried through by Paulling et al in San Francisco Bay between 1971 and 1974(7). There, all measured data were stored on digital tape for further evaluation; this is probably now the most comprehensive data base available on capsize events.

As long as a general solution of equation (1) is lacking and is confined solely to experiments, the moment balancing procedure turns out to be suitable from the theoretical and the practical points of view. Until better computing methods for modelling physical reality have been developed, the requirements of the hydrostatic balancing method should be met.

It is felt that an explicit inclusion of the roll motion into stability standards will rarely result in more stringent requirements. On the other hand, ignoring roll motion entirely would be quite unsatisfactory. Therefore, the static balancing method ought to be extended from implicit consideration of the roll motion to at least some sort of resonance criterion, since ship design practice cannot wait until the last problem in roll motion calculation has been solved.

(iv) In addition to roll motion and capsize experiments, there has been no lack of attempts to solve the roll motion equation (1) theoretically. So far, only solutions with different simplifications have been found. Although such solutions already supply some hints on how ship stability should be judged from the motion point of view, one cannot yet be satisfied with the current state of the art. The main reasons which make equation (1) intractable can be summarised as follows:

(a) For safety from capsize, extreme motion amplitudes must be studied. The equation of motion at large roll becomes non-linear.

(b) The time dependent excitation of roll motion is not confined to the right hand side exciting moment K (ϕ, t) in equation (1). It was first shown by Grim in 1952(8), that the time dependent variation of the restoring term F (ϕ, t) in equation (1) may result in severe roll motion resonance in following seas. This so-called parametric excitation has so far been treated by applying the Mathieu equation with sinusoidal variations of the metacentric height GM at small roll amplitudes:

$$J_T' \ddot{\phi} + g\Delta(GM + \delta GM \sin \omega_E t)\, \phi = K'(\phi) \qquad (3)$$

(c) Hydrodynamic parameters such as mass and damping terms for non-symmetrically shaped cross sections at large angles of heel using the strip method, or determined directly for the whole three dimensional hull are difficult to calculate, and only in recent years have computer programs

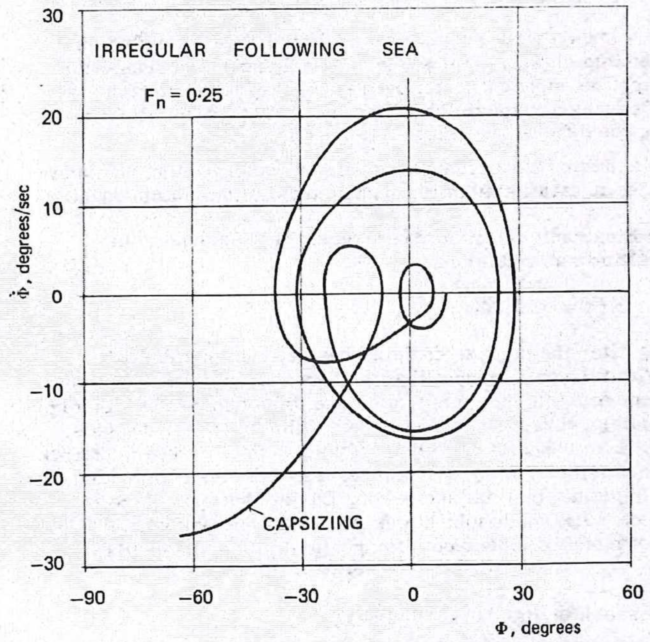


Fig. 2. Computed Sample of Stochastic Roll Motion Process Including Capsizing in the $\dot{\phi}\phi$ - Plane

been developed which might be applied(9,10). These use source distributions to evaluate the flow around the underwater ship body.

(d) The natural seaway excitation is not restricted to single harmonics, but appears mainly as a random stochastic process, which is described by means of spectral analysis. Because of the strong non-linearity of the righting arms at large roll amplitudes, the linear superposition principle using response amplitude operators is not applicable for extreme roll motion. From a numerical solution of motion equation (1) with random seaway excitation in following and stern quartering seas, motion criteria for avoiding capsize might be derived. In Fig. 2 is shown an example of a solution for a stochastic roll motion at random parametric seaway excitation, plotted in the $\dot{\phi}\,\phi$-plane(11). Capsizing occurs if the $\dot{\phi}\,\phi$ curve crosses a boundary circle in the outward direction. Such time domain solutions of the motion equation can only result from a numerical step by step integration and therefore the computing time required is substantial. With modern high speed computers, a computer simulation time of one twentieth of the real time for a ship prototype has already been reached, which makes the computational effort reasonable. Furthermore, a choice of significant severe environmental and ship conditions has to be made in order to reduce the calculation effort.

However, to date only qualitative agreement exists as to the stochastic motion pattern between simulation and real behaviour. Therefore in 1972 Abicht(12) developed a criterion based solely on solving the motion equation for the respective severe roll periods for a whole set of different initial conditions. From that he derived a probability index P for capsize, which might be used to compare different ship designs for their safety from capsize. Although this P-index is not identical with a measure of the real capsize probability, it might serve as a capsize criterion, as long as all relevant parameters are included.

In 1975 Kuo and Odabasi(13) proposed the application of Lyapunov's method, formulated in 1892, which is basically a generalisation of the stability definition for an equilibrium position according to Lagrange, to the stability of motion. Lyapunov functions describing the time varying total energy of the motion system have to be constructed, and the rate of change of energy with time is studied, giving information on the stability of motion. Although Lyapunov's method sets the foundation for a mathematical definition of motion stability, there still remains the problem of adequately estimating the Lyapunov functions.

Since roll motion in a random seaway is a stochastic process, there have also been attempts to derive some probabilistic motion properties analytically, such as by de Jong(14) and by Haddara(15). The phase plane curve $\dot{\phi}\,\phi$ as in Fig. 2 may be treated as a two-dimensional stochastic process. The conditional probability density for $\dot{\phi}$-ϕ, described by the mean and variance of the stochastic process, may be derived using the Fokker-Planck equation, which leads to similar results to those obtained with the equivalent linearisation technique. In our view, it has not yet been proved that such an approach really covers extreme rolling including instabilities of motion which result in capsizing.

With all this ambiguity on accurate motion modelling, and on the resulting stability criteria, a wide field remains open for further theoretical research work and for comparison with experiment. In any event both the ship designer and ship master cannot wait for results from increasingly sophisticated research; they need information and practical guidelines now.

Thus, for daily practice, we still recommend the balancing of heeling and righting arms instead of applying any sort of Rahola type criterion. For the calculation of the righting arm, hydrostatic variations in regular longitudinal waves should be considered. However, in order to cope with the dynamic effects involved in motion stability, this method should be supplemented by a resonance consideration.

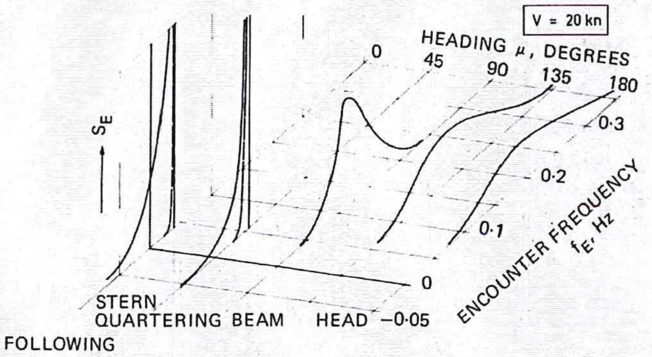


Fig. 3. Normalised Encounter Spectra Ship—Seaway versus Heading for Constant Ship Speed

Although we do not then try to estimate the expected roll amplitude and the probability of capsize, we should at least avoid dangerous situations where large roll angles may build up.

(v) The most dangerous situations appear in following and stern quartering seas; therefore beam and head sea considerations can be omitted. So far, resonance in a following seaway has only been treated for the linear case at harmonic parametric excitation, and the Mathieu stability charts can be used. In general, Mathieu resonance is to be expected at natural frequencies equal to natural multiples of half the exciting frequency

$$f_n/(0{\cdot}5 f_{exc}) = 1,\ 2,\ \ldots \tag{4}$$

Actually, the exciting frequency of righting arm variation in a random seaway is represented by the encounter spectrum of ship and seaway. It depends mainly on ship speed and heading, related to wave celerity of any partial wave within the wave spectrum, according to the following equation

$$\begin{aligned} f_E &= (c - V\cos\mu_W)/L_W \\ \omega_E &= 2\pi f_E = (\omega - k\,V\cos\mu_W) \end{aligned} \tag{5}$$

This transformation yields some Doppler effect in following and stern quartering seas, which means that the partial energy of short and long waves of the seaway spectrum at the same encounter frequency may be additive. This is demonstrated in Fig. 3, where a normalised encounter spectrum is plotted against encounter frequency and ship heading for one constant ship speed.

From equation (5) it is seen that the maximum of the encounter frequency is independent of the wave length

$$\text{Max}\ (\omega_E) = \frac{g}{4\,V\cos\mu_W} \tag{6}$$

This transformation as shown in Fig. 3 has one remarkable property. The minimum bandwidth of the encounter spectrum due to the Doppler effect appears always in a stern quartering sea.

The total energy of righting arm variations in the seaway due to the Doppler effect will be compressed into a very narrow encounter frequency band, thus being close to an almost harmonic excitation. Therefore, if the resonance condition according to equation (4) is met, severe roll may build up, generally from low cycle resonance, i.e. during a small number of rolls as a wave group passes by.

In 1965 Grim and Takaishi(16) presented results based on hydrodynamic calculations using strip theory, which showed that the exciting roll moment K in regular waves may well be greatest in quartering seas, and will be more severe for small metacentric height. Their results also underline the

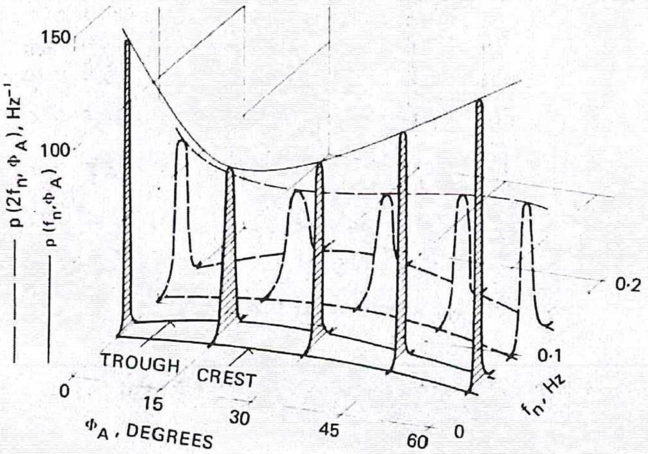


Fig. 4. Probability Density of Natural Roll Frequency in Following Random Seaway versus Roll Amplitude

importance of treating the safety of a ship from capsize in stern quartering seas more thoroughly.

But now the problem arises of how to define the natural roll frequency of a ship oscillating in random seas. From considerations of maximum kinetic energy equal to the maximum potential energy for a motion system without energy dissipation, an expression for the natural roll frequency can be derived as follows:

$$\omega_n(\phi_A, t) = \frac{1}{i_T' \, \phi_A} \cdot \sqrt{2g \int_0^{\phi_A} GZ\,(\phi, t)\, d\phi} \qquad (7)$$

for roll amplitudes ϕ_A within the positive range of GZ only.

Because of the non-linear shape of the righting arm curve, ω_n depends on the roll amplitude ϕ_A. Furthermore, the natural roll frequency ω_n in a seaway will again be a stochastic process, depending on the time varying righting arm GZ. The probability density of the natural roll frequency according to the phase conditions between the ship and the waves can be constructed approximately by calculating ω_n for a severe wave crest, a wave trough, and for the mean righting arm of crest and trough, and then assuming a normal distribution with its maximum at the mean, and crest and trough frequencies at $\pm 3\sigma$ respectively. The result based on the righting arm curves shown in Fig. 1 is depicted in Fig. 4 for different constant roll amplitudes ϕ_A. There is a substantial range of natural frequencies covered depending on either wave phase conditions—crest or trough or intermediate—or on roll amplitude.

From Fig. 4 it is immediately obvious that natural frequency considerations alone in the upright ship position cannot be sufficient. This can also be proved from measured encounter and roll motion spectra of ship models tested in San Franscisco Bay(17). Therefore, possible unstable resonance regions for the non-linear case must be developed in excess of the well known Mathieu charts.

According to equation (4) it now seems appropriate in a random seaway to avoid overlapping of the excitation encounter spectrum S_E (Fig. 3) in following and quartering seas with the expected range of natural roll frequencies described by the probability density p (f_n) and with the probability density of double the natural frequency p ($2f_n$), as in Fig. 4.

In constructing both—i.e. the encounter spectrum plane for the variations of the righting arm and the natural roll frequency plane depending on crest and trough righting arm curves—and by subsequent comparison, dangerous parametric resonance might be avoided during design or by changing heading and ship speed during operation, if appropriate tables are developed and made available to the ship master.

There might still be dangerous roll motion effects which are not yet covered by the suggested approach, which is based on treating the single degree of freedom equation (1) only. The influence of other degrees of freedom was shown by Paulling and Rosenberg in 1959(18). Kure and Bang in 1975 thoroughly studied an accident(19) where gyroscopic coupling effects were the cause of the capsize of a ship with high freeboard. Thus regions of ship parameters should be defined where coupling ought to be considered as well. Also the broaching-to mode of capsize related to severe yaw needs further study.

In 1974 Krappinger and Sharma(20) presented results of a statistical multivariate discriminant analysis of IMCO-gathered capsize data from ship accidents. A similar procedure applying parameters such as residual wave crest righting arms, range of positive righting arm etc. had been proposed using the data base from capsizing experiments such as measured by Paulling in San Francisco Bay(17). Here again statistical results will be more significant because of better known capsize conditions and a larger sample size of capsizes for the same type of ship.

2. SOME REMARKS ON THE SUBDIVISION OF TANKERS

by W. Abicht

2.1 The Probabilistic Method of Evaluating the Effectiveness of Watertight Subdivision

In accordance with a recommendation of the 1960 Safety of Life at Sea Conference, the effectiveness of watertight subdivision was investigated thoroughly over a number of years. The initiator of these studies was Wendel, who proved that there are shortcomings in the well-known factorial system of subdivision. He demonstrated(21) that a correct evaluation of subdivision is only possible if the randomness of location and extent of damage is taken into account.

In the following years, his method of judging the effectiveness of subdivision by estimating the survival probability was improved and simplified for practical application(22-24). The results were observed by the IMCO Sub Committee on Subdivision and Stability Problems, and in 1967 an ad hoc group was established which was entrusted with the development of new subdivision regulations for passenger ships on the basis of the probability concept. The work of this group was very successful. New formulae were set up, which allow the calculation for all 'floodable' spaces (spaces which can be flooded without causing the sinking or capsize of the ship) of the probability of being flooded in the case of side damage. The sum of these probabilities—the so-called 'Attained Subdivision Index'—represents the survival probability. It must at least be equal to the 'Required Subdivision Index', which is a function of ship length and the number of persons on board. The Sub Committee approved these new subdivision rules, and in 1973 they were adopted by IMCO as an equivalent to the old subdivision rules of the International Convention for the Safety of Life at Sea, 1960(25).

Ships, however, must not only be subdivided in order to withstand a limited flooding, but also in order to prevent a considerable outflow of harmful cargo. Disasters like the stranding of the TORREY CANYON have shown that for special types of vessels (oil tankers, chemical tankers, gas carriers etc.) the second safety aspect should even be given priority. Consequently, the effectiveness of subdivision of such ships should be judged by the probability that the pollution from the ship due to side or bottom damage will not exceed an acceptable extent. The calculation procedure corresponds with the determination of the survival probability. Instead of regarding the 'floodable' spaces, spaces are considered which contain oil or other kinds of cargo which may pollute the sea. Onerous additional calculations, such as damage stability calculations, by which it must first be determined whether or not a space is 'floodable', are not necessary. In the case of an oil tanker, it can be seen directly from the general arrangement plan which tanks are oil tanks and which are not intended for oil.

The similarity of the calculations of survival probability and pollution probability makes it desirable to have subdivision regulations for tankers which, like the new equivalent subdivision rules for passenger ships, are based on probability considerations. It is surprising that at the time when the probabilistic standard of valuation was introduced as an equivalent to the unsatisfactory factorial subdivision system, IMCO has adopted subdivision requirements for oil tankers which are deterministic in their assumptions and ignore the randomness of location and extent of side and bottom damage. Nevertheless, it is interesting to discover by application of the probabilistic method the real extent of improvement which is to be expected for tankers built according to these requirements(26).

Another problem which can be solved by application of the probability theory is the question of whether it is more effective to fit a tanker with a double bottom or with a double skin. Before entering into these considerations in detail, the fundamentals of damage probability will be reviewed in the following sections.

2.2 The Probability of Breaching a Ship's Compartment or Tank by Side Damage

For every region of a ship bounded by transverse and longitudinal bulkheads and the hull, the probability P can be calculated that it will be flooded in the case of side damage. The procedure is described in Ref. 24. For instance, for wing compartment a in Fig. 5, the conditions which must be fulfilled if the flooding is to be limited to this wing compartment can be stated as follows:

(i) the centre of damage must be located within the wing compartment

$$x_0 < x < x_0 + \ell$$

(ii) the longitudinal extent of damage must not exceed twice the distance between the damage centre and the nearest transverse bulkhead

$$y < 2(x - x_0) \text{ if } x \leqslant x_0 + \ell/2 \text{ or}$$
$$y < 2(x_0 + \ell - x) \text{ if } x \geqslant x_0 + \ell/2$$

(iii) the transverse extent of damage must not exceed the distance between the hull and the longitudinal bulkhead $t < b$.

From this it follows that in a Cartesian system of damage co-ordinates x, y and t, a prism with a triangular base can be drawn, comprising those side damages which would result in a flooding of the compartment under consideration (and only of this compartment!). This prism lies within a greater prism, representing the total region of all possible side damage. The dimensions of the greater prism are given by the limitations that no damage lengths are greater than the length of the ship, and no penetrations are greater than the breadth of the ship (Fig. 5).

Every point within the small prism represents a side damage causing flooding which is limited to the wing compartment a. The probability P that such side damage will occur depends on the statistical distribution of the damage coordinates or the 'probability density' f (x, y, t). The density function can be approximately determined by an analysis of the damage data which were collected by IMCO. The probability itself is obtained by evaluating the triple integral of the density function, which must be taken over the volume of the small prism(24):

$$P = \iiint_{\text{Vol.}} f\,(x, y, t)\; dx\; dy\; dt.$$

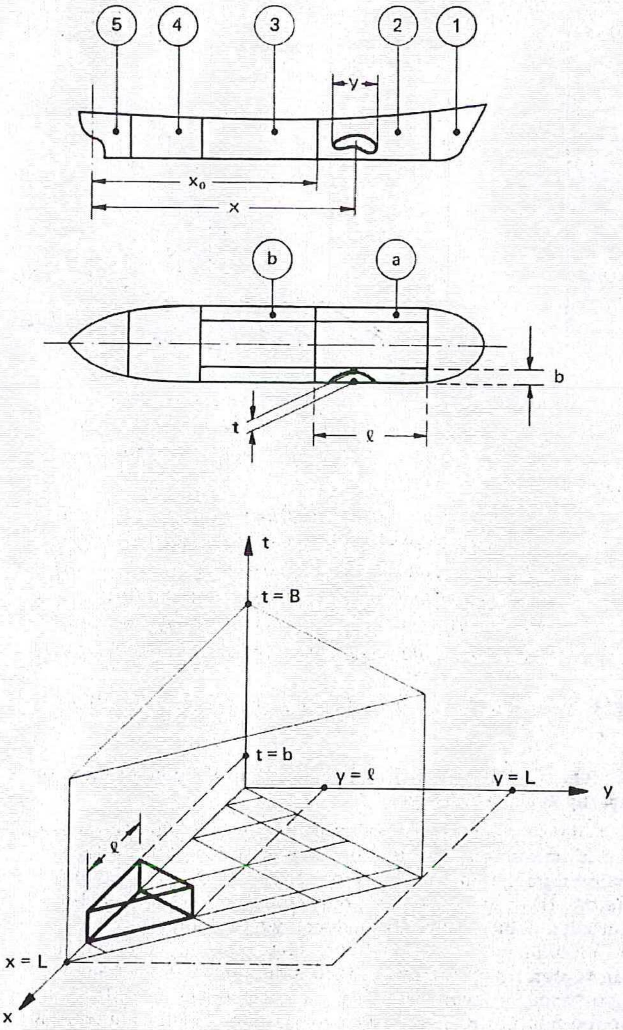
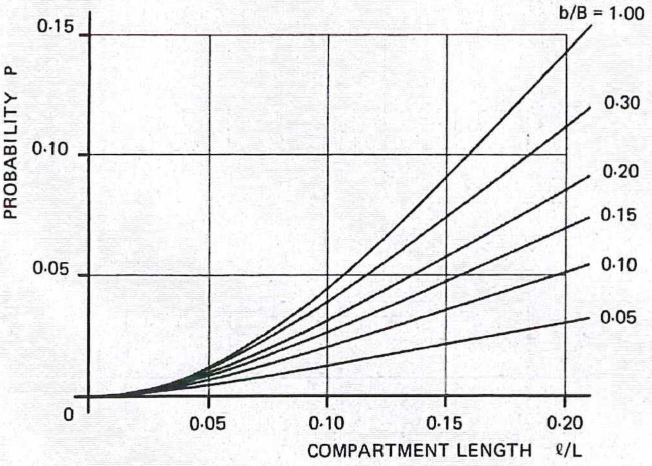


Fig. 5. Side Damage Co-ordinates x, y and t and Illustration of the Conditions for Flooding Being Limited to the Wing Compartment a

If the calculations are carried out systematically for different wing compartment lengths ℓ, different wing compartment breadths b, and different ship lengths L, families of curves can be plotted showing for each wing compartment of a ship (up to and including b = B) the probability that the space under consideration will be opened if any side damage occurs (diagrams for practical use are published in Ref. 24). Strictly speaking, the probability P also depends on the location of the compartment within the ship's length. This fact, however, can be neglected because there is no great difference between the frequency of side damage to the forebody and to the afterbody.

The influence of ship length on the probability P can be eliminated if the damage coordinates are made dimensionless: $\xi \equiv x/L$, $\eta \equiv y/L$, $\tau \equiv t/B$. Now, the density function which must be integrated is $f(\xi, \eta, \tau)$. By plotting the probability values, a new diagram $P(\ell/L, b/B)$ is achieved which is suitable for all ship lengths (Fig. 6). It must be noted, however, that application of this diagram to ships of $L > 200$ m is problematical because—for lack of statistical information about damage to large ships—it cannot be said whether the assumed density function is still valid. Finally, it should be pointed out that, in any case, only one kind of probability diagram must be applied: either the diagrams published in Ref. 24 or the diagram in Fig. 6. This is a consequence of the small differences between the probability values which are unavoidable if the damage data are represented in two different ways.



if $\ell/L > 0{\cdot}2$ and $b/B = 0{\cdot}05$: $P = 0{\cdot}03047 + 0{\cdot}1812\,(\ell/L - 0{\cdot}2)$
$\ell/L > 0{\cdot}2$ and $b/B = 0{\cdot}10$: $P = 0{\cdot}05113 + 0{\cdot}3199\,(\ell/L - 0{\cdot}2)$
$\ell/L > 0{\cdot}2$ and $b/B = 0{\cdot}15$: $P = 0{\cdot}06956 + 0{\cdot}4491\,(\ell/L - 0{\cdot}2)$
$\ell/L > 0{\cdot}2$ and $b/B = 0{\cdot}20$: $P = 0{\cdot}08561 + 0{\cdot}5689\,(\ell/L - 0{\cdot}2)$
$\ell/L > 0{\cdot}2$ and $b/B = 0{\cdot}30$: $P = 0{\cdot}11132 + 0{\cdot}7725\,(\ell/L - 0{\cdot}2)$
$\ell/L > 0{\cdot}2$ and $b/B = 1{\cdot}00$: $P = 0{\cdot}14286 + 1{\cdot}0714\,(\ell/L - 0{\cdot}2)$

Fig. 6. Probability Diagram for Side Damage (Ref. 27)

2.3 The Probability of Breaching a Ship's Compartment or Tank by Bottom Damage

From IMCO damage statistics it can be seen that the percentage of bottom damage is comparatively low: 76% of the total is side damage and only 24% bottom damage. It is doubtful whether these percentages apply for ship lengths greater than 200m, since there is evidence which indicates that bottom damage to large ships is somewhat more frequent than to small and medium-sized ships. Though of lesser importance, an evaluation of the effectiveness of watertight subdivision in the case of bottom damage is also interesting. It is particularly worthwhile to study the influence of the double bottom and its height on the degree of safety after grounding. The principles of evaluation are the same as those described in the preceding section.

According to the nature of bottom damage the regions of the ship which may be opened are bounded by bulkheads, a watertight deck (e.g. the tank top), and the bottom of the ship. To simplify matters, only three dimensions of the bottom damage will be considered (Fig. 7): location x (different from the definition of side damage location, the fore end and not the centre of damage marks the location), longitudinal extent y, and vertical extent z. Each of these damage coordinates must lie within a quantificable range if the flooding is to be limited to a certain space or a group of adjacent spaces. For example, the conditions for flooding the double bottom cell below compartment 2 in Fig. 7 are:

(i) the fore end of damage must be located within the length of the double bottom cell under consideration

$$x_1 - \ell < x < x_1$$

(ii) the longitudinal extent of damage must not exceed the distance between the fore end of damage and the after end of the double bottom cell

$$y < x - (x_1 - \ell)$$

(iii) the vertical extent of damage must not exceed the height of the double bottom

$$z < h$$

For reasons mentioned in the section above, it is advisable to make the damage coordinates dimensionless: $\xi \equiv x/L$, $\eta \equiv y/L$, $\zeta \equiv z/D$. In a three-dimensional coordinate system each bottom damage resulting in flooding of only one space or group of adjacent spaces is represented by a point which is located within a small prism with a triangular base (Fig. 7). Contrary to the corresponding prism for side damage (Fig. 5), the base of this prism has not the shape of an isosceles triangle but, as a result of the different definition of location, that of a right-angled triangle. This is also true for the great prism, which represents the total set of all possible bottom damage.

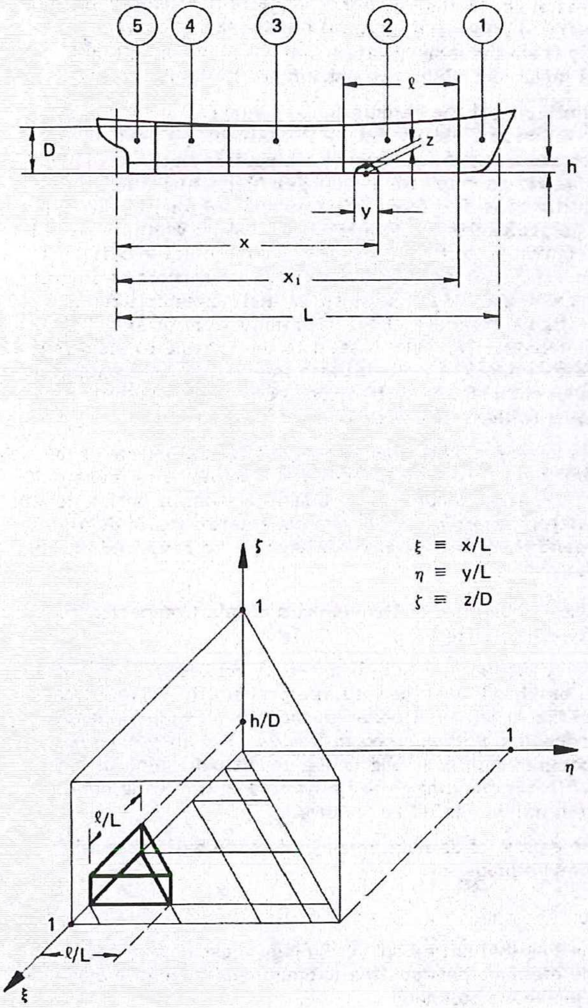


Fig. 7. Bottom Damage Co-ordinates x, y, z and Illustration of the Conditions for Flooding to be Limited to the Double-Bottom Cell Below Compartment 2

According to the frequency distribution of the bottom damage, a probability density $f(\xi, \eta, \zeta)$ can be assigned to each point within the great prism. Unfortunately, the information about bottom damage which can be obtained from IMCO damage statistics is rather poor and it is, therefore, impossible to determine this three-dimensional function in an explicit form. The probability P, however, can be calculated just as well if the equation for the two-dimensional density function $f(\xi, \eta)$ is known and the statistical information about the third damage component τ or ζ respectively is given by its distribution function (cf. Ref. 24). Of course, the density function $f(\xi, \eta)$ for bottom damage is different from that for side damage. For instance, bottom damage occurs much more frequently to the forebody than to the afterbody, whereas the frequency of side damage is nearly constant over the ship's length. So the probability that a space will be opened by bottom damage does not only depend on the length ℓ/L and the height h/D of the space under consideration, but also on the location x_1/L. Fig. 8 shows the results of systematic probability calculations which were carried out analogously to the probability calculations described in Appendix 3 of Ref. 24. On the left of Fig. 8, probability values are plotted which are valid for spaces of unlimited height (in practice there is no bottom damage higher than the depth of the ship). The right hand graph shows the corresponding diagram for spaces of lower height (h/D=0·2). The probability values for spaces with other h/D ratios can be obtained from diagrams published by Bruhn(28).

2.4 Evaluation of the Effectiveness of Tanker Subdivision

Avoidance of oil pollution has become such an important objective that tankers should be primarily subdivided with a view to minimising the discharge of oil in the case of damage. In order to meet this demand, the Convention for the Prevention of Pollution from Ships includes special subdivision rules for tankers. The question of how effective these provisions are in reality can now be answered by application of the probability diagrams. The procedure will be demonstrated by an example which is taken from Ref. 29.

Fig. 9 shows two tankers of equal deadweight (approx. 380,000 dwt) but with different subdivision. The tanker on the left hand side of Fig. 9 is subdivided conventionally, whereas the tanker on the right is provided with cargo tanks of limited size and with segregated ballast tanks according to the new IMCO rules. A survey of the different oil outflow properties of these tankers can be obtained by calculating for each cargo tank of both ships the probability P that the tank will be opened by side damage (values P from Fig. 6; bottom damage is not considered because it occurs more rarely; in addition to this it would cause only a partial outflow of the oil).

From the fact that the density of oil is lower than that of water, it follows that the oil in the cargo tank under consideration flows out completely, provided that the side damage extends from a point above to a point below the waterline. Hence, the sum of the probability values of all cargo tanks of the same capacity represents the probability that the sea will be polluted by a quantity of oil which corresponds to the volume V of such a tank. For the other tank sizes of the ship, the probability that the amount of oil outflow equals the tank volume can be determined in the same way. Of course, groups of adjacent tanks must also be regarded according to the existing probabilities that two or more tanks will be hit by the side damage. If these outflow probabilities are plotted against the amount of oil outflow,

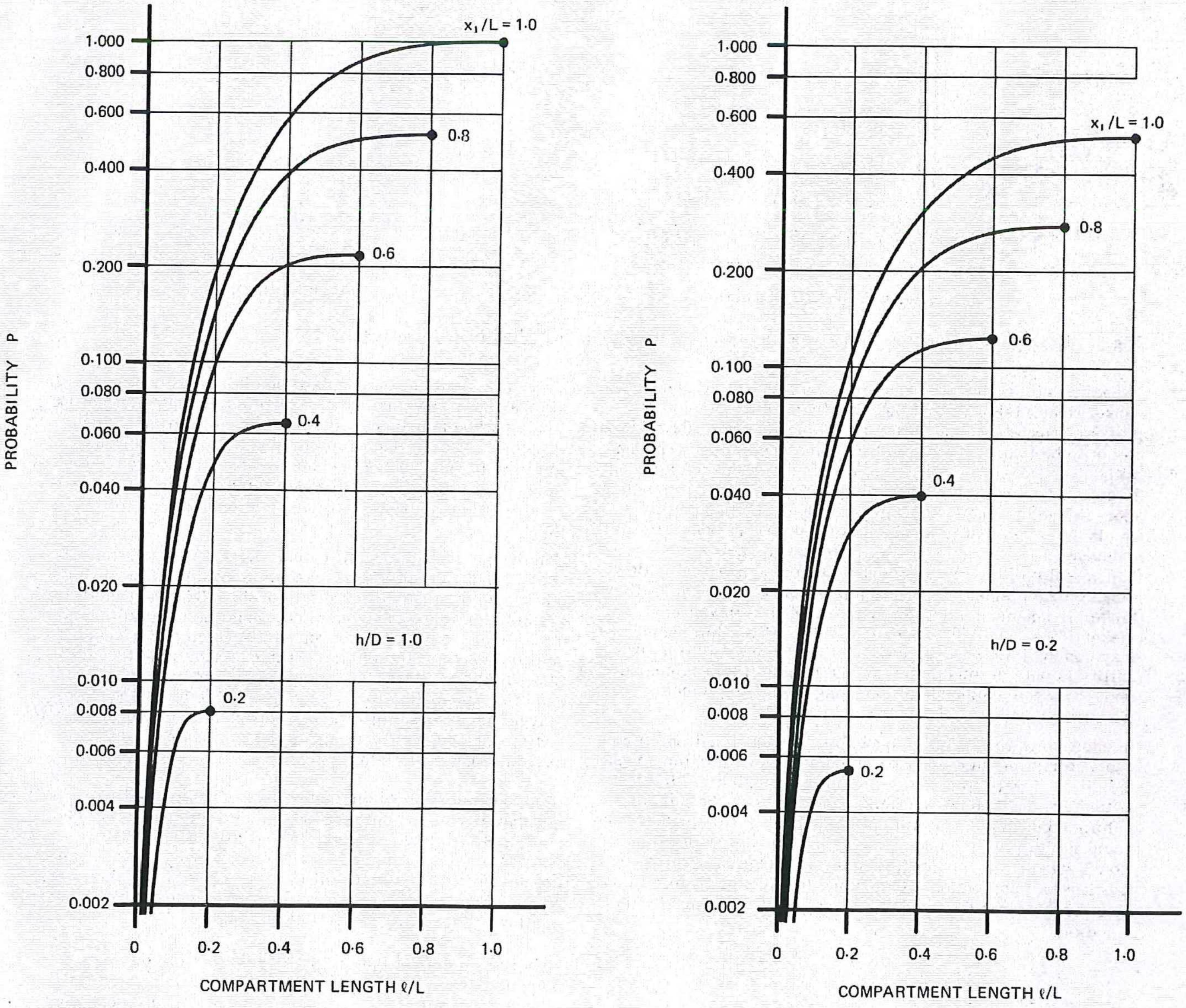


Fig. 8. Probability Diagrams for Bottom Damage (Ref. 28)

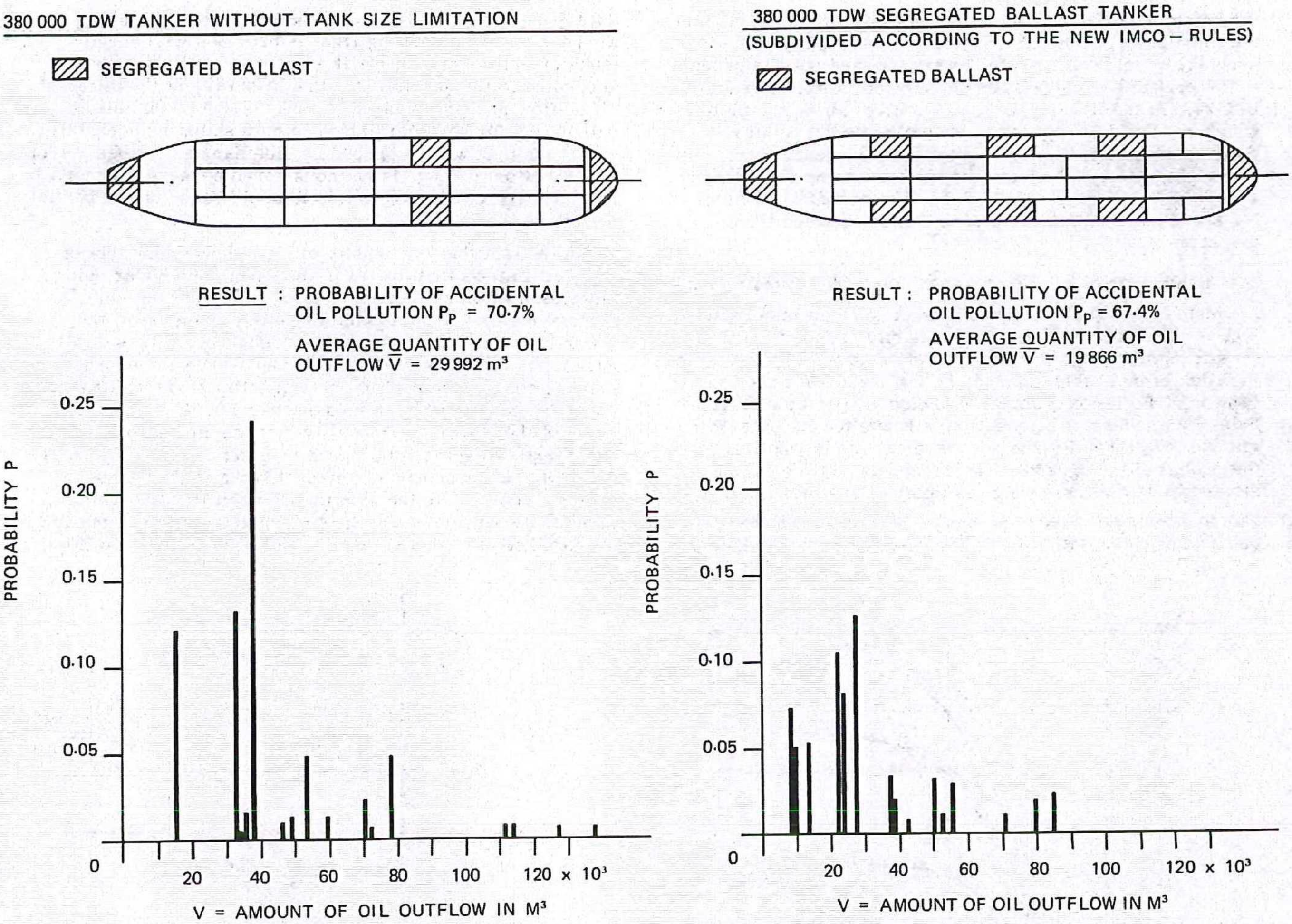


Fig. 9. Example Showing the Effectiveness of the New Subdivision Rules for Oil Tankers

we gain a clear picture of the effectiveness of the respective tanker subdivisions. For instance, from the diagrams in Fig. 9 it can be concluded that an oil outflow of $>100 \times 10^3$ m^3 is not to be expected if the IMCO rules are applied, whereas without tank size limitation the probability for such an event is approximately 3% (0·8% + 0·8% + 0·7% + 0·7%). Furthermore, by adding the outflow probabilities, the probability P_P can be obtained that an accidental oil pollution occurs at all, independent of the amount of oil discharge. It is interesting that in spite of the arrangement of three segregated ballast tanks on each side, the pollution probability P_P of the IMCO tanker is not much smaller than that of the conventional tanker (67·4% and 70·7% respectively). From this result we may conclude that a greater reduction of the pollution probability is only attainable by a construction which is characterised by the avoidance of carrying oil in wing tanks (double skinned vessel).

In addition to the pollution probability P_P, at least one further characteristic value must be calculated in order to express the oil outflow properties of a tanker numerically. In view of the fact that efforts are made not only to avoid any oil pollution but also to minimise the amount of oil outflow when accidental pollution occurs, the average quantity of oil outflow $\bar{V}$ will be an appropriate additional index for the effectiveness of subdivision. Regarding the amount of oil outflow as a discrete random variable, $\bar{V}$ can be determined by the equation

$$\bar{V} = \sum_{i=1}^{n} V_i P_i$$

where n is the number of discrete oil quantities which may flow out. Application of this formula to the two tankers in Fig. 9 shows that the new IMCO rules are more effective than may be assumed, if the effectiveness of tanker subdivision is solely judged on the basis of the pollution probability. In consequence of the tank size limitation, the mean amount of oil outflow of the IMCO tanker is only two thirds of that of the conventional tanker (19,866 m^3 instead of 29,992 m^3).

Unfortunately, this result cannot be generalised. Ref. 29 shows that the oil outflow properties of IMCO tankers of the same size can differ considerably. The best method of eliminating these shortcomings would be to establish completely new subdivision regulations which are based on probability considerations. Nevertheless, it is true that the IMCO rules will lead to a decrease of accidental oil pollution and that, according to the higher subdivision standard of large tankers, the differences between the oil outflow properties of a conventional and an IMCO tanker of the same size increase with ship size.

Another question which can be answered by application of the probability diagrams refers to the effectiveness of double bottoms. Aiming at a reduction of oil outflow in the case of bottom damage, efforts were made towards the installation of double bottoms in all oil tankers. The favourable effect of the double bottom is confirmed by the results of investigations carried out in the United States(30-32).

There is no doubt that, in the case of bottom damage, the double bottom has an effect which is similar to that of the double skin in the case of side damage. From the economic point of view, however, to fit all tankers with both subdivision

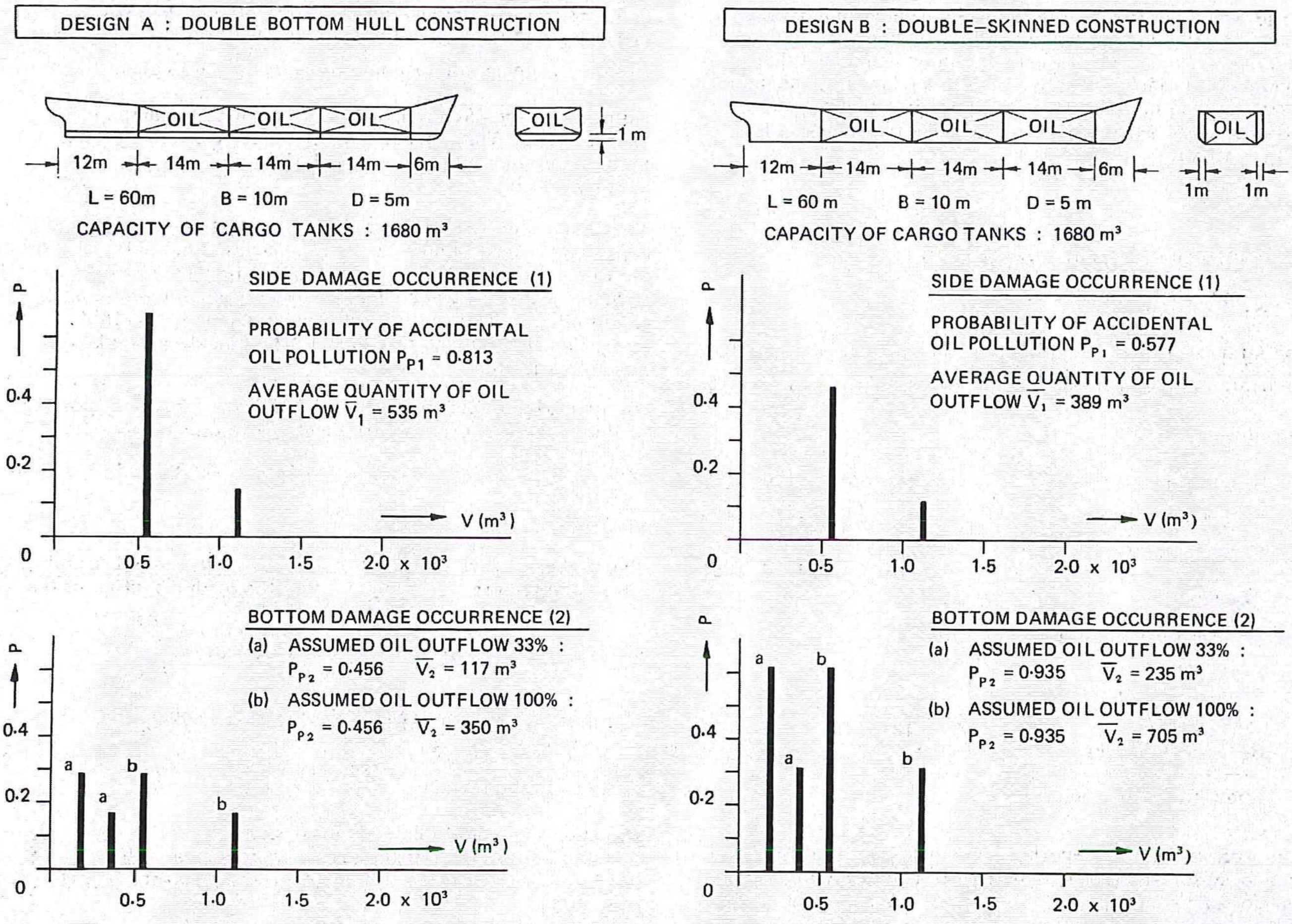


Fig. 10. Example Comparing the Effectiveness of Double Bottom and Double Skin

elements would seem to be too severe a demand. Hence, the point is not whether or not a double bottom should be installed, but which of these constructions is to be preferred.

Each of the two concepts—double bottom and double skin—results in an increased steel weight. Considering that the depth of tankers is only about half the beam, the differences between the additional weights will be smaller than may be expected. Furthermore, side or bottom voids respectively can be arranged in such a way that the loss of cargo tank capacity will also not differ greatly. Therefore the total rise in cost can be kept within the same limits, and the problem is reduced to the question of whether the double bottom or the double skin construction has the better oil outflow properties.

In order to judge the effectiveness of each of these alternative constructions, the outflow probabilities of a tanker fitted first with a double bottom (design A) and then with a double skin (design B) have been calculated. For the sake of clarity and in view of the doubts which may arise when the probability diagrams are applied to ships greater than 200 m in length, a comparatively small tanker has been chosen. The centreline bulkhead has been omitted (Fig. 10). Assuming the occurrence of side damage as well as bottom damage, the outflow probabilities can be determined for design A and design B by using the probability diagrams (Figs. 6 and 8). The results are presented in Fig. 10*.

Unlike side damage, bottom damage causes only a partial outflow of the tank contents. The reason for this is that a hydrostatic balance between the oil and water is generally reached after a small quantity of oil has escaped. The real amount of oil discharge, however, can be greater—depending on the state of the sea—because of the action of dynamic forces. Therefore two assumptions have been made:

(a) one third of the tank contents flows out, and

(b) the entire tank empties.

For a final judgement, the results obtained separately for side and bottom damage must be combined in such a way as to take account of the fact that 76% of the casualties are caused by side damage and 24% by bottom damage. The procedure is fairly simple (the values in brackets are applicable if a total oil outflow from the tanks opened by bottom damage should prove to be more realistic):

Design A

$$P_p = 0{\cdot}76\ P_{p1} + 0{\cdot}24\ P_{p2} = 0{\cdot}727$$

$$\overline{V} = 0{\cdot}76\ \overline{V}_1 + 0{\cdot}24\ \overline{V}_2 = 435\ \text{m}^3\ (491\ \text{m}^3)$$

Design B

$$P_p = 0{\cdot}76\ P_{p1} + 0{\cdot}24\ P_{p2} = 0{\cdot}663$$

$$\overline{V} = 0{\cdot}76\ \overline{V}_1 + 0{\cdot}24\ \overline{V}_2 = 352\ \text{m}^3\ (465\ \text{m}^3)$$

Comparing these final results, it can be stated that both valuation standards—the pollution probability P_p as well as the average quantity of oil outflow $\overline{V}$—indicate clearly the superiority of the double skin construction. Of course, this statement is only applicable to the tanker under consideration, but there is every reason to believe that a similar

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*Details of the calculation are given in the authors' replies to the discussion.

result would be expected in the case of most small vessels. It remains to be proved whether this finding will also hold for large tankers. At any rate, it can be concluded that the double skin is more effective than is assumed by the authors of Ref. 30, who inferred from their studies that 'double bottoms are of such great effectiveness that there is no justification for a double skin'.

3. A SHORT NOTE ON FREEBOARD

by K. Wendel

The International Convention on Load Lines 1966 stipulated the basic minimum freeboard for Type B ships with $\frac{L}{D} = 15$ as follows:

L	Length (m)	25	50	100	150
F_b	Freeboard (mm)	208	443	1271	2315
$\frac{F_b}{L}$	$\frac{\text{Freeboard}}{\text{Length}}$ (%)	0·83	0·89	1·27	1·54

that means approximately

$\frac{F_b}{D}$	$\frac{\text{Freeboard}}{\text{Depth}}$ (%)	12	13	19	23
$\frac{\nabla_R}{\nabla_D}$	$\frac{\text{Reserve buoyancy}}{\text{Buoyancy up to depth}}$ (%)				

It is well known, but nevertheless surprising, that the basic freeboard for ships of length 25 m is relatively smaller than that for ships of e.g. 150 m length. At the beginning of the discussions about a minimum freeboard, naval architects preferably considered the ratio of reserve buoyancy and the height of the working platform above the load line. Our professional forebears required an overproportionate increase of the freeboard. They did this as the result of observations and reports from seamen about the dangers a person on deck had to contend with if green seas were shipped in rough weather(33, 34).

Freeboard is also of great importance for intact stability, for subdivision and stability in damaged conditions, but one should not assume that such considerations were of great influence to the freeboard tables. Such tables were first compiled in England by Rundell and Martell and later on, when the 'Plimsoll' mark became statutory, they were used for the assignment of load lines(33, 34).

These tables stipulated the overproportionate increase of basic freeboard, and though some amendments were made (mostly reductions of the table values) this increase has been retained up to the present, Fig. 11(35).

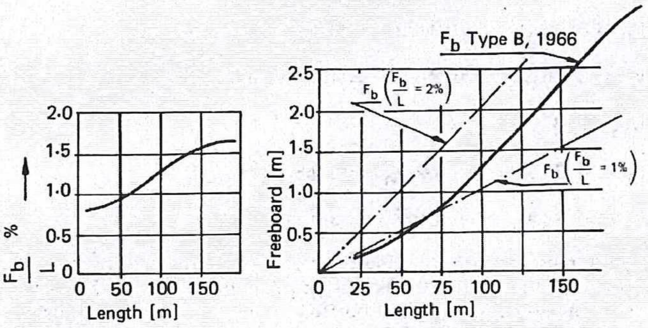

Fig. 11. Overproportionate Increase of Freeboard (1966 Convention, Type 'B' ships)

Many experts on the subject of 'safety at sea' demand greater basic freeboard for ships of small and average size, and they propose for example to raise $\frac{F_b}{L}$ up to about the value which the 1966 Convention prescribes for ships of 150 m length. Their arguments are mostly based on the motions of ships in waves, especially pitching and heaving(36-38).

There are other experts who have also tried to explain the overproportionate increase of freeboard by the motions of a ship in waves. They say that a small ship goes up over the waves, but that a larger ship has to go through them or it would pitch more heavily(39). The author believes this is an optical illusion and that model experiments would be senseless if this were true.

An approximate physical explanation of the higher proportion of the reserve buoyancy with length or in other words increase of $\frac{F_b}{L}$ in the freeboard tables may be given as follows(41):

The higher a wave the greater is its energy, and half of this energy is kinetic. The velocity v in the orbital motion of the water particles will increase proportionally to $\sqrt{\frac{L_{W1}}{L_{W2}}}$, if L_{W1} and L_{W2} are the lengths of waves with equal slope or ratio $\frac{\zeta_W \text{ (wave height)}}{L_W \text{ (wave length)}}$. A seaman who clings to rails or stanchions is able to hold, by muscular strength, about F = 100 kp (220 lbf). If the area A which he sets against the force of the wave is 1/2 m², then the pressure on his body will be

$$F = \tfrac{1}{2} \rho\, C\, A\, v^2 = 28 \frac{\text{kp s}^2}{\text{m}^2}\, v^2$$

$$\left(\rho = 102 \frac{\text{kp s}^2}{\text{m}^4},\ C = 1{\cdot}1,\ v\left[\frac{\text{m}}{\text{s}}\right]\right)$$

He would be able to hold on up to a velocity of v = 1·9 m/sec.

The orbital velocity near the surface of the wave is $v = \frac{2\pi}{T}\,\frac{\zeta_W}{2}$. We assume that the part of the wave crest which is flooding over the deck has this velocity and that friction and obstacles are neglected as is the speed of the ship. With $\frac{\zeta_W}{L_W} = \tfrac{1}{20}$, $T = \frac{L_W}{c}$ and the wave velocity $c = \sqrt{\frac{gL_W}{2\pi}}$ we get $v = 0{\cdot}2 \frac{\text{m}^{1/2}}{\text{s}} \sqrt{L}$, with L substituted for L_W, since heavy seas breaking over the deck are about ship length. We find that with a ship length of 85 m the bearable velocity which could strike a seaman, and be withstood by him in a breaker, is about 2 m/sec or 7 ft/sec.

This bearable limit will be attained for 25 m length if we add a ship speed of only two knots. To prevent persons from being lost overboard, it is certainly sensible to increase the freeboard overproportionately against the length.

Perhaps this note will draw attention to the forces which occur when green seas overflood the upper deck. Modern knowledge about the behaviour of ships in waves enables us to determine the frequency of deck wetness, and will perhaps, one day, help us to ascertain the size of the overflowing breakers(40, 42-45).

4. CONCLUSIONS

Although in recent years our general understanding of the capsize phenomenon has broadened, mainly due to intensive experimental research and numerical studies of the roll motion equation at large amplitudes, there still remain problems on the best fit to physical reality. Therefore, besides the task of improving motion stability calculation schemes, there is a need to simplify calculations by checking for the most important parameters and to derive sound roll motion stability criteria for application in practical ship design work.

For this purpose, balancing uprighting and upsetting moments of a ship is advocated, taking into account variations of righting arms in a seaway. In random seas, the most dangerous parametric roll motion excitation has to be expected in waves from the stern quartering direction, mainly due to the Doppler effect in transforming wave frequencies to the moving ship. It is suggested that roll motion dynamics should be included in a stability analysis by constructing encounter frequency spectra depending on ship speed and heading, and natural roll frequency distributions with respect to the phase conditions between ship and waves, and with respect to the roll amplitude, in order to account for the non-linearity.

Although there are still unsolved problems in the theory of ship rolling in waves, it would not be advisable to delay practical stability recommendations until the last problem has been solved. Safety of life at sea is too important a consideration and does not justify further neglect of the progress which has been made during recent years.

Compared to safety from capsize, the prevention of accidental oil pollution is quite a new problem which has arisen in the course of the rapid growth in tanker size. It is known that a reduction of accidental oil pollution can be achieved by appropriate subdivision of tankers. For practical purposes, it is desirable to have a standard of valuation which enables the designer to judge the oil outflow properties of a tanker. Appropriate criteria can be obtained if the location and extent of damage are regarded as random quantities. For each oil tank, the probability P_i that its contents V_i will flow out can then be calculated. The sum of the outflow probabilities represents the pollution probability P_p in case of hull damage. Furthermore, the mean amount of oil outflow $\overline{V}$ can be determined by the equation $\overline{V} = \sum_{i=1}^{n} V_i P_i$. Both quantities, pollution probability P_p and mean outflow $\overline{V}$, indicate the effectiveness of the subdivision with respect to accidental oil outflow.

By application of the evaluation standards P_p and $\overline{V}$ it can be shown that the new subdivision rules for oil tankers are not as effective as they could be if they were based on probability considerations. It can also be shown that a reduction in accidental oil pollution can be obtained by adequate tank size limitations as well as by a double skin or double bottom. As to the effectiveness of the double skin, it was deduced that this construction may be more effective than the installation of a double bottom. This finding is contrary to the results of a study carried out recently in the United States.

Many experts criticise the low minimum freeboard of small vessels prescribed by the Load Line Convention. The overproportionate increase of freeboard was considered necessary on account of observations and reports from seamen. This tendency can be confirmed by a physical explanation showing that the forces from waves washing over the deck and acting on persons and structural members increase proportionally to the ship length. It is suggested that these forces should not be ignored in future studies of freeboard.

NOMENCLATURE

ϕ	angle of roll
$\dot{\phi}$	angular roll velocity
t	time
N	damping moment
F	restoring moment
K	exciting roll moment
Δ	displacement mass
g	gravity acceleration
GM	transverse metacentric height
GZ	righting lever
J'_T	transverse moment of inertia
i'_T	transverse radius of gyration
c	wave celerity
V	ship speed
μ_W	heading, angle between wave component direction and ship's course
L_W	wave length
$k = \frac{2\pi}{L_W}$	wave number
ω	circular frequency, s^{-1}
f	frequency, Hertz
$f_n = \frac{\omega_n}{2\pi}$	natural frequency, Hertz
f_{exc}	exciting frequency
ϕ_A	roll amplitude
S	spectral density
p	probability density
E	subscript for encounter
σ	standard deviation

The other symbols can be understood from the context in which they are used.

REFERENCES

1. Rahola, J.: 'The Judging of the Stability of Ships and the Determination of the Minimum Amount of Stability', Dissertation, Helsinki, 1939.
2. Wendel, K.: 'Bemessung und Überwachung der Stabilität', Trans. Schiffbautechnische Gesellschaft, Vol. 59, 1965.
3. 'Recommendation on Intact Stability for Passenger and Cargo Ships under 100 metres in length' and 'Recommendation on Intact Stability of Fishing Vessels', IMCO, London, 1968.
4. Arndt, B.: 'Ausarbeitung einer Stabilitätsvorschrift für die Bundesmarine', Trans. Schiffbautechnische Gesellschaft, Vol. 59, 1965.
5. Kastner, S.: 'Kenterversuche mit einem Modell in natürlichem Seegang', Schiffstechnik, Vol. 9, 1962.
6. Kastner, S.: 'On the Statistical Precision of Determining the Probability of Capsizing in Random Seas', International Conference on Stability of Ships and Ocean Vehicles, Glasgow, 1975.
7. Paulling, J. R., Oakley, O. H. Jr. and Wood, P. D.: 'Ship Capsizing in Heavy Seas: The Correlation of Theory and Experiments', Int. Conf. on Stability of Ships and Ocean Vehicles, Glasgow, 1975.
8. Grim, O.: 'Rollschwingungen, Stabilität und Sicherheit im Seegang'. Schiffstechnik, Vol. 1, 1952.
9. Söding, H.: 'The Flow Around Ship Sections in Waves', Schiffstechnik, Vol. 20, 1973.

10. Webster, W. C.: 'The Flow About Arbitrary, Three-Dimensional Smooth Bodies', Jnl. of Ship Research, Vol. 19, No. 4, 1975.

11. Kastner, S.: 'Das Kentern von Schiffen in unregelmäßiger längslaufender See', Schiffstechnik, Vol. 16, 1969 and Schiffstechnik, Vol. 17, 1970.

12. Abicht, W.: 'On Capsizing of Ships in Regular and Irregular Seas', Int. Conf. on Stability of Ships and Ocean Vehicles, Glasgow, 1975.

13. Kuo, C. and Odabasi, A. Y.: 'Application of Dynamic Systems Approach to Ship and Ocean Vehicle Stability', Int. Conf. on Stability of Ships and Ocean Vehicles, Glasgow, 1975.

14. De Jong, B.: 'Some Aspects of Ship Motions in Irregular Beam and Following Waves', Report No. 175 S, Netherlands Ship Research Centre TNO, Delft, 1973.

15. Haddara, M. R.: 'A Modified Approach for the Application of Fokker-Planck Equation to the Non-linear Ship Motions in Random Waves', Int. Shipbuilding Progress, Vol. 21, No. 242, 1974.

16. Grim, O. and Takaishi, Y.: 'Das Rollmoment in schräglaufender Welle', Schiff und Hafen, Vol. 17, 1965.

17. Kastner, S.: 'Analysis and Evaluation of Capsizing Experiments in San Francisco Bay 1971', Dept. of Naval Architecture, University of California, Berkeley, March 1973.

18. Paulling, J. R. and Rosenberg, R. M.: 'On Unstable Ship Motions Resulting from Non-linear Coupling', Jnl. of Ship Research, Vol. 3, No. 1, 1959.

19. Kure, K. and Bang, C. J.: 'The Ultimate Half Roll', Int. Conf. on Stability of Ships and Ocean Vehicles, Glasgow, 1975.

20. Krappinger, O. and Sharma, S. D.: 'Sicherheit in der Schiffstechnik', Trans. Schiffbautechnische Gesellschaft, Vol. 68, 1974.

21. Wendel, K.: 'Die Wahrscheinlichkeit des Überstehens von Verletzungen', Schiffstechnik, Hamburg, April 1960.

22. Krappinger, O.: 'Einfluß von Tiefgang, Flutbarkeit, Stabilität und Seegang auf die Beurteilung von Unterteilungen', Jahrbuch STG, 1961.

23. Robertson, J. B.: 'Subdivisions of Ships as Related to Survival Probability', Unpublished paper presented to IMCO, 1966.

24. Wendel, K.: 'Subdivision of Ships', Appendix by Abicht and Bakenhus, SNAME Diamond Jubilee International Meeting, 1968.

25. Robertson, J. B., et al: 'The New Equivalent International Regulations on Subdivision and Stability of Passenger Ships', Trans. SNAME, Vol. 82, 1974.

26. International Conference on Marine Pollution: International Convention for the Prevention of Pollution from Ships, IMCO, London, 1973.

27. Sulkiewicz, H.: 'The Probability of Oil Pollution from a Tanker in Case of Hull Damage', (in German). Diploma thesis, Institut für Schiffbau, Hamburg, 1973.

28. Bruhn, H.: 'The Effectiveness of Watertight Subdivision in Case of Bottom Damage', (in German). Diploma thesis, Institut für Schiffbau, Hamburg, 1972 (published in HANSA 1972).

29. Abicht, W., Kastner, S., Wendel, K. et al: 'The Effects of the IMCO Regulations for the Prevention of Pollution by Oil on Design and Construction of Oil Tankers', (in German). Report for the Federal Ministry of Transport, Hamburg, 1975 (an abridged version was published in HANSA 1975).

30. Porricelli, J. D., Keith, V. F. and Storch, R. L.: 'Tankers and the Ecology', Trans. SNAME, Vol. 79, 1971.

31. Porricelli, J. D. and Keith, V. F.: 'Tankers and the US Energy Situation, An Economic and Environmental Analysis', Marine Technology, October 1974.

32. Card, J. C.: 'Effectiveness of Double Bottoms in Preventing Oil Outflow from Tanker Bottom Damage Incidents', Marine Technology, January 1975.

33. Barnaby, K. C.: 'The Institution of Naval Architects, 1860-1960', RINA, London, 1960.

34. Wendel, K.: '75 Jahre Schiffbautechnische Gesellschaft 1899-1974', Hamburg, 1974.

35. International Conference on Load Lines, 1966.

36. Manley, C. V.: 'A Fifty Years' Survey of Casualties to Merchant Ships Reported Abandoned, Foundered or Missing', Trans. INA, Vol. 92, 1950 (also papers in 1951, 1958 and 1959).

37. Schnadel, G.: 'Ocean Waves, Freeboard and Strength of Ships', Trans. INA, Vol. 80, 1938.

38. Skinner, H. E. and Phillips, J.: 'Merchant Ship Subdivision', Trans. INA, Vol. 91, 1949 (also papers by Skinner in 1951 and 1959).

39. Neuerburg, E. M.: 'Freeboard in the Design of Merchant Ships', Haarlem, 1953.

40. Krappinger, O.: 'Freibord und Freibordvorschrift', Trans. Schiffbautechnische Gesellschaft, Vol. 58, 1964 (containing 56 further references).

41. Wendel, K.: Contribution to discussion of Ref. 40.

42. Bakenhus, J.: HANSA 1964, S. 2207-2217.

43. Ochi, M. K.: 'Extreme Behavior of a Ship in Rough Seas—Slamming and Shipping of Green Water', Trans. SNAME, Vol. 72, 1964.

44. Lewis, E. V.: 'Principles of Naval Architecture', 1967.

45. Cleary, W. A. jr: 'Load Lines—The Lever of Safety', Trans. SNAME, Vol. 83, 1975.

DISCUSSION

J. Strating: Dr Kastner has indicated that there are some deficiencies in the Rahola type of stability approach. In my opinion, in the Wendel approach where the balancing of moments is used there are deficiencies also. One cannot say that comparison of heeling moments in still water is essentially better than making an indirect comparison of stability moments and corresponding stability predictions based on accident statistics. May I ask what exact reasons Dr Kastner can give to confirm his own conclusion that the Wendel method is better than Rahola's? Is this conclusion based on statistical information, for instance?

Studies on uncoupled equations of ship motions do not make sense when non-linearities are taken into consideration. In that case Abicht's method whereby severe ship motions near the natural frequency of rolling are considered will not always be useful. Perhaps I should speak of the natural frequencies of rolling because this frequency of rolling depends on wave height, for instance, when non-linearities are taken into account.

Experiments in beam waves with a model of a small fishing vessel performed at Delft University of Technology have shown that capsizing seldom occurs near the natural frequency of rolling, not even when wave heights are extremely high and the metacentric height of the vessel extremely low (20 cm, for instance). On the other hand, capsizing did occur frequently at wave frequencies somewhere between the natural frequency of rolling and the natural heaving frequency. This can possibly be explained by strong non-linear coupling effects between sway, heave and roll. Consequently, analytical solutions of the uncoupled equation(1) will not be very useful for beam sea conditions.

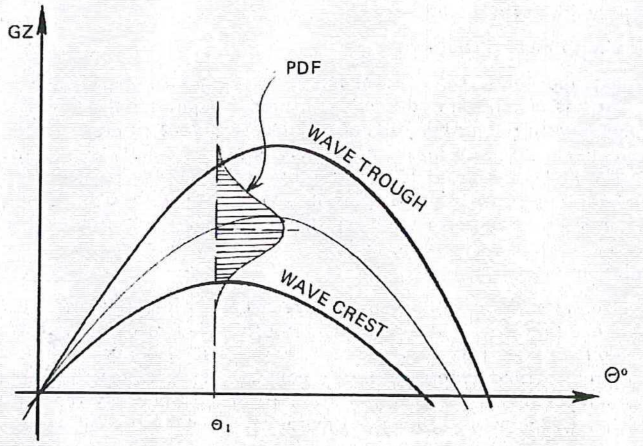

Fig. 12

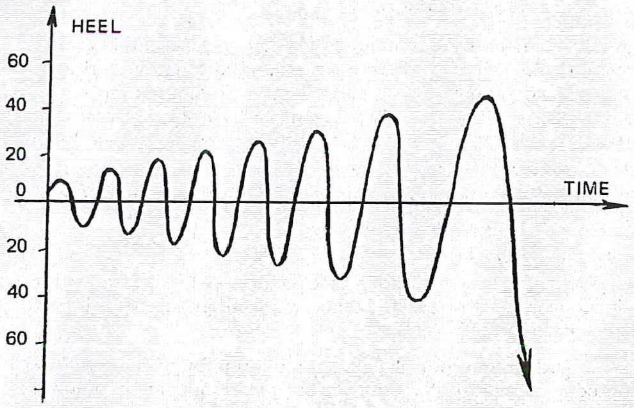

Fig. 13

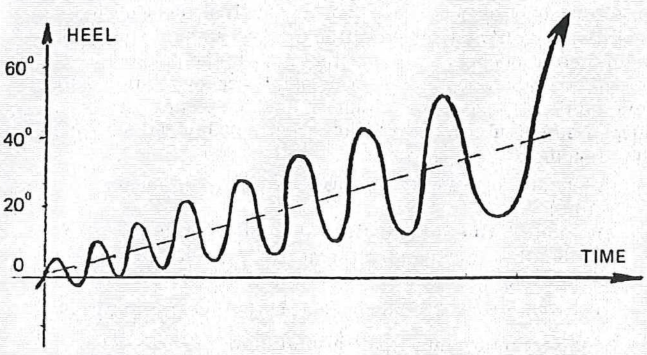

Fig. 14

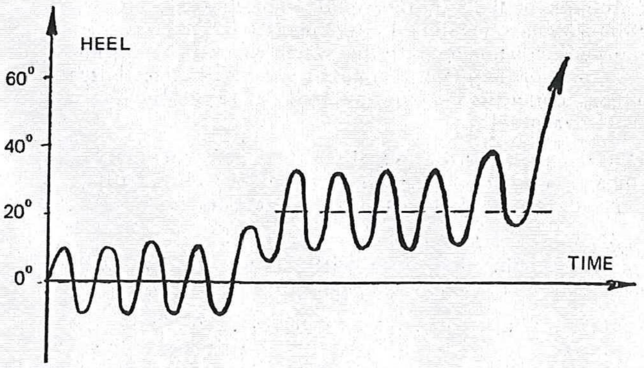

Fig. 15

Besides new efforts in mathematical modelling, suitable experiments have to be designed to study all the effects I have mentioned, because the occurrence of capsizing is obviously more complicated than indicated in the paper. Under extreme conditions it is pointed out that viscous effects are very important and may even dominate the whole problem. Suitable methods have to be designed to predict the viscous damping. This will complicate mathematical modelling considerably.

Eugene C. Haciski: My discussion is addressed to the first part of this paper. As a ship designer and stability rule proposer, I have a few remarks about the application in daily practice of recent scientific findings and recommendations in the field of ship stability and seakeeping as presented in this excellent paper.

Scientists have divided opinions about the philosophy of development of stability criteria based strictly on the probability of capsize. In spite of great progress in recent years in the development of methods using theory and experiments, stability failure prediction is far from practical solution. I also have in mind my experience with the 'Capsize' computer program which uses the numerical ship motion time domain simulation program developed by Dr Paulling and his team. The results of this program depend very significantly on the coefficients of the initial condition of ship motion and initial wave characteristics. It is extremely difficult to determine these coefficients because they are products of random variables which are statistical in nature. In my opinion, sampling of statistical data of real ship casualties and near-casualties (wave spectra and ship motion) may help considerably in the selection of coefficients needed for simulation program input with an improved degree of confidence. This collection of data could be achieved by descriptive and numerical recording similar to the methods used for many years in commercial aviation.

The authors' recommendation for the righting arm calculation of applying a hydrostatic variation in regular longitudinal waves is very interesting. Ignoring time domain of ship and wave motion, we can obtain a large range of righting arm curves. However, due to realistic sea state variation during the life-time service of the vessel, some curves would be more probable than others. In general, the diagram may be depicted by probability distribution functions at each angle of heel, see Fig. 12.

To keep consistency in the validation of 'energy' balance and stability assessment, a similar approach should be adopted in solving problems regarding the heeling forces. There is another problem here not only in variation of deterministic values, but also in the proper and most probable selection of unfavourable combinations of the forces induced by the following factors: wind pressure, seaway resonance, rudder, passengers crowding on one side, green water on deck well, dry cargo shifting, free surface effect, non-symmetrical icing, forces generated by special equipment (fishing gear, dredging equipment, cargo lifting equipment, towing, cable laying, etc), loading and unloading at sea, error in KG assessment.

Next, I would like to make some small amplification of this paper and stress certain characteristics of ship rolling motions just before the capsizing point.

Fig. 13 shows a classical case, where the amplitude of heel angle increases gradually up to the critical point, after which the vessel capsizes. It should be noted that rolling motion is symmetrical, in other words, the ship returns to the upright position in each period of roll. In this case the ship motion is probably in resonance with wave-induced forces, and damping moments are not effective.

Fig. 14 illustrates another typical group of ship rolling motions. It is characterised by the gradual increase of amplitude with the centre line of oscillations diverging from the zero line, with steady or variable slope.

Fig. 15 shows a very interesting group of ship rolling motions with semi-steady heel angle. This characteristic phenomenon of ship roll is also known as the pseudostatic heel angle, or the quasistatic heel angle.

Finally, it would be proper to defend the ABS 1973 rules and the US Coast Guard proposed regulations regarding the stability of semi-submersibles. The author's statement at the bottom of page 95 contains a small discrepancy: the methods of heeling and righting energy balance in hydrostatic manner, used in the regulations referred to, are not a Rahola type approach.

L. K. Kupras: I have a few general remarks to make on Dr Abicht's paper. If we want to discuss the effectiveness of the watertight subdivision of ships, we have to pay more attention to the problem of the impact energy which can be absorbed by the hull construction. The extent of any damage depends on the ability of the hull structure to absorb the impact energy.

We can expect that, adopting a special construction topology, the extent of the damage can be reduced in length and in width. It is a problem which can be very important for roll on/roll off ships with more than 12 passengers on board. We know that for this type of ship, longitudinal watertight sub-division is preferable, but in most cases the distance between the longitudinal bulkhead and the side is required to be as small as possible. Knowledge of the possible extent of damage is based on statistical data which concern typical construction from the past.

Can we design new and equivalent structures which will allow us to put the longitudinal bulkhead closer to the ship's side? I expect that such construction would be heavier and more expensive, but what is the price to be paid for the lost lives and polluted seawater? I think we can learn something from the ideas and experience of automobile factories. For example, Volvo cars are equipped with strong buffers and soft and energy-absorbing fronts, backs and sides. They are rather expensive but 'safe' cars. Why not think about 'soft' ship bows and impact energy absorbing ship sides?

H. Bird: I should like to congratulate the three authors of this group of papers which are useful, well written and were well presented.

Dr Kastner's paper
Dr Kastner has stated his objections to the Rahola type of stability criterion and I should like to agree with him. This type of criterion was a wonderful achievement when it was developed by Dr Rahola about 40 years ago but in my opinion it has served its purpose. The 1968 IMCO Recommendations are almost identical which is perhaps not surprising since a similar analysis technique was used.

Specific objections which I can think of are:

(i) It is now being applied to ship types, including offshore vessels and even, by some, to floating platforms, for which it was never intended and is unsuitable.

(ii) It gives no indication of the degree of safety or lack of safety, in relation to:
   (a) ship size
   (b) ship type, ie. its physical characteristics
   (c) sea and weather conditions.

Casualty investigations reveal these weaknesses.

(iii) It is inflexible.

A new IMCO Working Group, of which I am Chairman, was formed in 1975 to develop improved stability regulations. We have found it difficult enough to formulate a work programme to say nothing of solving the many associated problems. It was agreed that the means open to us to pursue our studies are as follows

(iv) Study of casualties, to determine modes of capsize (rarely possible due to lack of reliable witnesses).

(v) Systematic model experiments.

(vi) Ship motion theory.

I fully appreciate the difficulties associated with non-linear equations of motion and long term model experiments and I agree with the author, therefore, that the issue to ship designers of better information should not be unduly delayed. At the last meeting at IMCO in February this year it was agreed that some form of weather criterion should be adopted as an interim solution. Many alternative criteria of this type are available and the problem is to agree on the best one.

The moment balancing method suggested in the paper and proposed by Professor Wendel is not familiar to me. What advantage does this have over the conventional energy balance method which we in this country recognise as Moseley's theorem? It is not clear to me in what way the author proposes to allow for the energy imparted to the ship by the waves. In the classical method, this is based on roll amplitude, either estimated or assumed, and is the corresponding potential energy. The wave trough curve in Fig. 1 does not appear to be used.

Fig. 3 is reasonably clear but Fig. 4 appears to need some further explanation. I would have expected a unique value of natural roll frequency at infinitesimally small amplitudes with the dispersion increasing proportionally with amplitude. The figure shows maximum variance about 15°, then decreasing thereafter. Why is this?

We shall study this paper further in UK and communicate with the author in due course.

Dr Abicht's paper
I read this paper with a good deal of interest. I am familiar with the work of the IMCO ad hoc working group of which I was Chairman 1967-1972.

I agree with the author that it seems surprising that IMCO adopted a deterministic solution to tanker outflow problems when the physical causes of inflow or outflow are the same. I feel that it was decided mainly as a matter of convenience to ship designers, Classification Societies, etc.

Dr Abicht may not be aware that at the first meeting in 1968 of the IMCO Sub-Committee on Ship Design and Equipment a proposal was put forward by the Japanese delegation based on Professor Wendel's theory which was very similar to what the author is now proposing. They suggested calculating two hypothetical outflow values which they termed:

(a) Expectative Value of oil outflow (fictitious mean value).
(b) Absolute Value of oil outflow (actual volume corresponding to a low compartment group probability—to be agreed).

The idea was eventually abandoned by the Sub-Committee.

It is comforting to know that the IMCO method can substantially limit oil outflow even though the probability technique might well have done it more effectively.

Dr Abicht's analysis of the relative merits of double bottoms versus double skins seems plausible but is dependent on damage statistics which can vary with time. This, however, is one of the main advantages of statistical methods in that they can follow accident trends and be updated at intervals.

I tend to agree with Dr Abicht that both safety and pollution avoidance regulations should be modelled on probability methods since collision damage is a random event.

Professor Wendel's paper
I enjoyed reading this paper but I am not sure if it was intended to be taken too seriously.

I find it difficult to accept the theory that the required freeboard is in any way related to sailors clinging to guard rails. I doubt whether the people who drafted the 1966 Load Lines Convention had such subtle ideas in mind.

I think the relative freeboard should logically be 'S' shaped, as it is, and flattened at both ends but I also feel that the variation with length is perhaps too severe and should have a higher ratio for small ships which more often get into trouble.

I suspect the shape has something to do with the sinister influence of a committee at work which inevitably involves compromises. Remember the story of the committee which tried to design a horse and ended up with a camel!

A. Lee: This interesting paper makes clear one view of the authors—that although they are pursuing a strongly mathematical programme of research they do not see results coming out of it in the near future. My comments may therefore already have occurred to them in the course of their studies.

My first point concerns the authors' scepticism that the Fokker-Planck equation can be used in assessing the probability of any particular motion of the ship. I share their scepticism about the Fokker-Planck equation being relevant to the problem. Having given the equation some attention, I decided some time ago that it could be of little use since the existing theory for it requires any excitation terms involved to be white noise generally. The sea wave force is not white noise. I would be interested in hearing the authors' comments on this.

My second point concerns equation (1). I think it should be pointed out that the difficulty lies not in solving it for any particular chosen form but in proving that it really represents ship motion at all. Such an equation is often called a 'model'. Unfortunately the question of whether it is a good model or a bad model is normally ignored.

I fully agree that in its presented form equation (1) is almost impossible to solve, but for a particular ship it would be possible to put some numbers in as the equation coefficients, and obtain a solution numerically.

Thus the real difficulty is not in solving equation (1) but in finding out if it is a good model for ship motion. There is at present no convincing argument which suggests this. I therefore ask the authors whether they have constructed any such argument or whether they have given attention to such an equation merely because it looks general enough to be plausible.

A. Yücel Odabasi: I would like to commence by paying tribute to the authors, in particular to Professor Wendel, for their valuable contributions to the understanding and assessment of ship stability over the past years. My comments will mainly be concerned with the first part of the paper.

Although agreeing with most of the views of my friend Dr Kastner I feel compelled to make the following remarks:

(i) As is well known, intact ship stability is mostly a small ship problem and the masters and skippers of these ships are either not equipped with the knowledge or they do not have time to use complicated stability information. Since an over-simplified study of intact ship stability is not expected to produce realistic predictions, it is necessary to develop two sets of criteria; one for ship designers and the regulatory bodies which will be comprehensive and convincing, and one for ship masters and skippers which will be extremely simple and related only to simple physical quantities such as freeboard, trim etc.

(ii) Although Dr Kastner seems to believe that sea conditions other than following and stern-quartering seas are insignificant, our experience does not show the same result. His conclusion generally holds for medium size coastal ships (approximately 50 to 70 metres in length). For smaller vessels, in particular for small fishing boats, beam seas are at least as dangerous as following and stern-quartering seas.

(iii) Admittedly both the Rahola type and the weather criteria type approaches have a lot of shortcomings. However, the method proposed in this paper also has its own deficiencies, for the following reasons:

(a) The theoretical wave form, even for the deterministic waves generated in model tanks, is quite different from the assumed wave form around the hull because of wave diffraction and wave radiation. Computations illustrate that such an assumption causes an over-estimation of the stability loss. This feature has been illustrated in Ref. 46 which indicated that for a ship 140 metres in length the maximum righting arm loss is as much as 0·5 metre (1·67 ft). This result indicates that if a ship of that length travels with a wave of the same length it will almost surely capsize, which is in contrast with reality.

(b) The method of determining the stability loss when the wave crest is at amidships is not unique(47) and the use of three alternative methods indicates different losses.

(c) Although steady wind action produces a statical heeling moment, the effects of wind gusts and shipping water are certainly dynamical and hence these actions cannot be treated as illustrated.

(iv) Stability regions related to parametric resonance can be improved by using the results of linear systems with random parameters(48). A generalisation of the results of Ref. 48 has been made by the present contributor(49) and it was found that the damping of the rolling motion has a very significant role in determining the stability regions.

It appears from Professor Wendel's analysis of determining the freeboard that in the calculation of the forces generated by shipping of water the relative motion between the ship and the wave is not considered. If this factor is taken into account the derived results may become different.

Before closing this contribution, I would like to make a few remarks in relation to the comments of the two previous contributors. The information presented by the gentleman from the US Coast Guard was very interesting and clearly indicates that the numerical solution procedure is not a useful way of predicting the stability of motion, a point which was raised by the present contributor, (49,50). As to Mr Lee's comment that the Fokker-Planck equation is applicable for white noise excitation only, he must be misinformed. Any classical textbook on stochastic processes shows that this equation can be used for Markovian processes which are substantially more general than white noise processes, see Ref. 51.

REFERENCES

46. USSR Delegation: 'Application of the Parameters Chosen as Possible Stability Criteria', IMCO, IS /IV/5, 1964.
47. Upahl, E.; 'Betrachtungen über Stabilitäts verfahren in Seegang', in two parts, Schiffbautechnik, 1961.
48. Bertram, I. E. and Zarachik, P. E.: 'Stability of Circuits with Randomly Time-Varying Parameters', Proc. Int. Symp. on Circuit and Information Theory, Los Angeles; IRE Trans., CT-6, 1959.
49. Odabasi, A. Y.: 'Techniques for Assessing Stability of Ships and Other Floating Objects', Schiffstechnik, 1977, to appear.
50. Odabaşi, A. Y.: 'Ultimate Stability of Ships', Trans. RINA, Vol. 119, 1977, p. 237.
51. Kushner, H. J.: 'Stochastic Stability and Control', Academic Press, 1967.

J. McCallum: I am directing my remarks principally to Dr Abicht, although I am saving up a little at the end for Professor Wendel.

I have read the part of the paper dealing with probability and clearly I have not spent enough time on it, because I do not really fully understand it yet. But a low probability of accidental oil pollution must certainly be better than a high one, and to that extent I follow Figs. 9 and 10.

But then I run aground again. Fig. 9 is easy in terms of outflow, but Fig. 10 shows that in the bottom damage to the double-skin ship, the 100% outflow is 705 m^3. But in the text immediately below, it says, I think, that 100% means that the entire tank empties, and that would be 1680 m^3. And then with the double-bottom construction for side damage only 535 m^3 runs out at 100% outflow, which is curious because the entire tank is again 1680 m^3.

Now I am in another quandary about the bottom damage (in the same case) with 100% outflow. With the double-bottoms empty there would not be any outflow if the damage did not pierce the inner bottom. But, in fact, there is, there is 350 m^3, so the double-bottoms are full of oil.

Well, that relieves me a great deal. What worried me most about the double-bottom proposal for tankers was that I had assumed they would be empty, and that could only mean for me that twice the number of tankers would then be on risk for explosion hazards than we have today. At the moment it is almost entirely the tankers in ballast. But nobody, in my opinion, has yet foolproofed a double-bottom space under a cargo tank against traces of gas.

So, Dr Abicht, I am confused and I rely on you to clarify some of the difficulties.

I was interested to read Professor Wendel's remarks on the holding power of a seaman against the orbital velocities of sea waves. I have done some investigation on sea waves myself over the past year or two and I have to confess that I am quite unable to reconcile the heavy weather damage to guard rails and other deck components in gales of Force 8 upwards with the bending moments which would result from the stagnation pressures applied by the orbital velocities.

I wonder if the seaman would still be holding on when the guard rail came away? And is it not a rather massive assumption that the wave length is the same as the ship length? If you have opportunity, just have a look at the picture of the derrick post of BENCRUACHAN after her tussle with the sea.

C. Boie: I should like to make some remarks on Dr Kastner's paper. During the whole of this Conference we have heard about risk analysis, risk management and probabilistic approaches to secure ship's safety. During the last two decades in all fields of ship safety—for instance, sub-division, structural design, etc—the methods used have changed dramatically and the results of recent research work have been taken into consideration. Only in the field of stability do most of the national and international authorities remain in the state of the art as it was in 1939 and base their rules on the Rahola criterion. I will not disqualify the valuable work of Rahola, but I feel that the authorities which issue stability rules sometimes believe that he obtained more comprehensive knowledge than he in fact had. Rahola did not write a bible, and the authorities should therefore study what he really did. He collected a number of official investigations of capsize accidents of the 1920s and 1930s. His statements are valid only for ship types of that time and not for newly developed types.

I made a similar collection of more recent stability accidents which was published in 1965 in an STG paper. This showed a number of important facts not to be found in the thesis of Rahola.

Recalculation of the stability of older ships showed that in nearly 50% of the cases the results of more modern calculation methods differed considerably from the original values.

In about 70% of the cases the influence of longitudinal or oblique waves was important. This influence cannot be considered by the so-called dynamic criterion which is based on the area under the smooth water righting lever curve.

Under Professor Wendel we have a coaster model test which clearly showed that a ship of a certain stability will not capsize in transverse waves but will do so in longitudinal or oblique waves.

The heeling moments in certain cases were higher than those which could be associated with stability curves which meet the Rahola criterion.

The results of the statistical investigation which I made and of the large number of accident investigations carried out by colleagues of Professor Wendel indicated clearly that a reliable stability criterion cannot be based on righting levers alone, that a balance of righting and heeling moments or levers is the only way to ensure that new and unknown types of ships or ocean vehicles can be made safe against capsizing, and that the influence of longitudinal or oblique waves on the righting levers is of great importance to stability and to the motions of the ship.

So I can only assist Dr Kastner in the way shown in his paper by saying that future stability rules must consider the possible heeling moments and the real influence of waves and not that of dynamic behaviour in smooth water. That this can be done in practical rules has been shown by the stability rules of the German and Dutch Navies (see, for instance, the STG publication of Arndt, 1965). It is necessary to do further calculations, but in the age of the computer these can be done at reasonable cost and in a short time.

B. N. Baxter: The authors state that the Rahola type approach to stability requirements, i.e., the derivation of a minimum value of GZ requires only a limited amount of calculation to be carried out and this is one reason for its retention.

The method proposed by the authors requires a static comparison of all righting and heeling moments including the calculation of variations in the hydrostatic righting arm when in regular longitudinal waves. If these calculations are lengthy presumably computer programs are available?

Although the latter approach is believed to be the more correct, all standards of stability suffer from the inability to link accurately criteria based upon static assumptions with those which should take into account dynamic effects at sea.

International requirements for standards of stability, whether based on the Rahola or Wendel proposals will result finally in the calculation of ship dimensions and shipbuilders and shipowners would be very interested to know, for example, what difference there is in the dimensions of ships with similar deadweights resulting from the application of the two standards of safety.

Safety at sea is too important to wait for legislation based on the known solution of all problems. It is better to derive standards now and deliberately allow some margin for the unknown dynamic effects and as time passes and knowledge increases, this margin can be reduced if it is seen that the application of an apparently too severe standard provides only marginal benefits.

M. Huther: I wish to thank the authors for their analysis of the difficulties presented by transverse motion calculations. I thus welcome the good excuse it gives me to explain to my seniors why some such calculations give poor results.

We consider, like the authors, that it is necessary to apply these methods and to expand them, in order to allow for improvement and to help in achieving safer design of ships.

The authors point out the difficulty of calculation which requires the use of time step methods. In Bureau Veritas we have begun to use analogical computing to evaluate transverse motions. I should appreciate knowing if the authors have any experience concerning such methods. In particular we observe that, due to small roll damping, transient motions do not disappear rapidly; so we ask ourselves if this could also be a possible explanation for large motions without true resonance in irregular seas.

I would appreciate the authors' views concerning small scale model tests. Do they consider that Froude similitude is sufficient, in particular for rolling, where damping is a very important parameter?

To conclude, I should like to emphasise that it may be difficult to establish new regulations in the near future to replace those now in operation. However, I agree with the necessity to follow the development of studies such as those described by the authors.

V. Kostilainen: First I should like to express my gratitude to Professor Wendel and Drs Abicht and Kastner for their very valuable work in this area. I have a comment to make on Dr Kastner's paper. I agree with him that we should include motion analysis of ships in stability regulations, but there are practical difficulties. In my experience, we do not at present have enough information on waves and winds, especially in shallow and narrow waters, and then we always have the human aspect as to how to handle the ship in critical situations. What we really need is an efficient system of collecting data on all ship accidents; then we shall know how to apply theoretical methods.

WRITTEN DISCUSSION

A. Morrall: I would like to begin by congratulating the authors most warmly both for their interesting presentation and for their valuable contribution to this most important problem of ship stability.

In my opinion the best way of developing improved intact stability criteria is to select simplified models, of possible modes of capsizing, and to relate them to certain deterministic conditions. This approach is of course very difficult to pursue due to the complexity of specifying the correct physical relationships and as a result this suggestion is unlikely to produce a short term solution. However, this approach avoids the use of direct definition of *sufficient safety against capsizing* by using instead a set of physically based conditions for a set of stability criteria.

The more simple approach to stability is to use properties of the righting moment curve as in the IMCO recommendation. The prescription of minimum values for the righting levers—as used by IMCO as well as the difference between righting and heeling levers—as advocated in the paper—are, in my opinion both based on the same safety concept in which only certain physical properties are prescribed and not however, the safety. Both these measures, it should be noted, are based on experience of one form or another. In view of these remarks I would like to ask the authors why they are surprised to find that the stability rules for semi-submersibles are based on the balancing of righting levers—while the authors themselves advocate the balancing of righting levers for ships—as shown in Fig. 1. In this connection could they explain the logic of subjecting a vessel to wind heeling moments when poised on a wave crest?

On page 98 the authors suggest a method to avoid dangerous parametric resonance which I find interesting but could the authors illustrate this method more clearly by using an actual vessel as an example and carrying out the necessary calculations? The authors might find that this method lends itself to graphical presentation of the results for a whole range of ship parameters which might be of general interest to ship designers. Could the authors comment on the accuracy of the roll prediction method advocated and would this be better obtained from statistical recordings of roll taken from a number of ships to give a cumulative probability distribution of roll amplitude?

Finally could the authors give their views on whether the general instabilities of the rolling motion are more dangerous than normal resonance?

AUTHORS' REPLY

Dr S. Kastner: Due to lack of time during the discussion, only in this written reply will I be able to answer all the points that have been made. First of all, I wish to thank the discussers for their valuable and helpful comments. The interest they have shown in many details of the stability problem makes it worthwhile to continue to grapple with the subject.

Mr Strating asked for the exact reasons why the Wendel method should be better than Rahola's. Although in his time Rahola's work was quite important, I do not think we should further rely entirely on accident statistics. Rahola's method does not account for different ship types under various external conditions whereas the method of moment balancing does.

Although moment balancing is purely hydrostatic, the required residual righting arms in waves were determined from model capsizings in irregular seas, which enabled samples to be taken at a larger rate than by waiting for full scale accidents. Furthermore, it is certainly closer to reality when examining all heeling effects against the righting arm curve.as Cleary at the Glasgow Stability Conference 1975 pointed out 'which may logically be considered of sufficient magnitude'. This is just the basic idea behind Wendel's approach.

With regard to motion calculation, so far even six-degrees-of-freedom motion simulation does not yet represent roll motion accurately enough for prediction. Nonetheless, simulation studies have been useful even for an uncoupled roll motion equation with nonlinearities. My own calculations showed good agreement with measured modes of capsizing in a following irregular seaway(11).

Surely other modes of capsizing such as broaching-to, or quartering or beam seas, require an approach which includes coupling effects. My suggested resonance check is intended for following and stern quartering seas only.

Of course, calculating stability and setting up rules is a much wider and more difficult field than I could cover in this paper; so I singled out one particular aspect, that is, the parametric (Mathieu) excitation in a random seaway.

Mr Haciski drew attention to the difficulties arising from capsizing calculations with a six-degree-of-freedom simulation program, which still render it inapplicable for practical stability failure prediction. But even with improvements it will be worthwhile to single out some specific dangerous conditions rather than trying to cover all possible ship motions. Although full scale accident statistics may be helpful, they cannot be considered sufficient from a statistical point of view(6).

Mr Haciski further points out different unfavourable combinations of external forces met during a ship's lifetime. To allow for these without too much computational effort seems to me to be the main advantage of moment balancing. Supplemented by the resonance consideration, it was successfully applied in studying the car ferry accident to HERAKLION in the Mediterranian in 1966(52).

I am glad Mr Haciski mentioned the different probabilities for the range of righting arm variations in a following seaway. Fig. 12 illustrates exactly the way I used the righting arm curves shown in Fig. 1, assuming a normal distribution, as described in the paragraph following equation (7).

The three different characteristic extreme roll motion modes shown by Mr Haciski seem to apply to regular waves. Similar modes have also been measured, among others, in irregular waves, see examples published in some of the cited papers(5,7,17). I agree with Mr Haciski's objection to my label 'Rahola type' approach in the ABS stability rules for semi-submersibles, which is rather a modified wind heel criterion. My intention was to put it close to Rahola, in order to stress the need for a more detailed stability analysis. Since writing my paper, results of semisubmersible stability research have been published (53).

I would like to thank Mr Bird for his clear comments on the Rahola approach. I am convinced that much detailed work on checking and comparing the proposed stability requirements and criteria is needed, and I am sure that the recently established working group will make progress towards agreeable new stability requirements.

The moment balancing method as applied to Navy regulations was published 1965 at the STG by Arndt (4) and Wendel(2), preceded by a paper in 1958 (54) and put forward to FAO in Rome in 1960 (55). In these regulations, the mean of the crest and trough righting arms is to be compared with the heeling moments. For most hull forms, this mean is below the still water righting arm curve. However, I did not show the mean in Fig. 1, but used the crest and trough only for calculating the natural frequencies, as shown in Fig. 4.

In Fig. 4, the variance of the roll frequency is related to the range of variation between crest and trough in Fig. 1. Thus both have their maximum variation at about 22° of heel, but only the density curves for every 15° were plotted in Fig. 4. At infinitesimally small roll amplitudes the gradient GM of crest and trough curves was used.

Actually, Equation (7) stems from a quasilinear system with the same potential energy as from the area under the righting arm curve up to the angle ϕ_A.

More precisely, the natural roll frequency results from

$$\int dt = \int \frac{d\phi}{\omega}\text{, yielding } \omega_{nat} = \frac{\pi\sqrt{2g}}{2\,i'_T} \cdot \frac{1}{\int_{\sigma}^{\phi_A} \frac{d\phi}{e(\phi_A)}}$$

with

$$e(\phi_A) = \int_0^{\phi_A} GZ(\phi)\, d\phi.$$

Numerical tables for the exact integration were given by von den Steinen in 1934 (56).

As I see it, the advantage of moment balancing over energy balancing is that it enables a good picture of the moments involved to be obtained, while saving integration of righting arm areas. Of course, some residual area of the righting arms has to be required in either case, via moment balancing or Moseley's theorem.

Finally, although I have suggested a check on the possibly large energy transfer from waves to ship by resonance, the energy actually imparted is not calculated. For dangerous resonance situations I would suggest roll motion simulation combined with model experiments.

Mr Lee's comments on mathematical ship motion modelling via equation (1) are appreciated. Certainly, the problem is a question of the correct numbers to be used as the equation coefficients. This is still quite cumbersome for capsize modelling, and even more for the verification of the coefficients by conducting model experiments.

My scepticism about the Fokker-Planck equation stems from the fact that the $\dot{\phi} - \phi$ distribution does not represent capsizing satisfactorily. With regard to restrictions on white noise this might not be so serious as Dr Odabasi has pointed out in his contribution.

Dr Odabasi stressed that safety from capsizing is mainly a small ship problem. Although beam seas should not be disregarded completely, they will in general be less dangerous than following or oblique waves. I am aware of the pitfalls of an oversimplified criterion. This is the reason I suggested an extension of any quasistatic approach to include at least some resonance criterion.

Wave diffraction and radiation could also be included in the approach advocated. Many years ago, we decided to calculate hydrostatic righting arm curves in waves without accounting for trim. There should be some agreement on the procedure in order to make the results comparable.

Neither calculation nor measurements could show that wind gusts impinging upon a ship within the frequency range required would be sufficient to produce a large dynamic heel. Therefore it seems reasonable to treat wind heel in a static manner. Again, for smaller ships this assumption becomes less valid.

Shipping water also has an hydrostatic effect. We have a research project under way on the dynamics of water impact in relation to freeboard within the Research Pool 'Sonderforschungsbereich 98' for Ship Technology at Hamburg and Hannover.

I agree with Dr Odabasi that damping should be included in a parametric resonance consideration of roll motion. In solving for roll motion, however, extreme roll and capsizing is certainly a domain where linear analysis does not apply.

Regarding Dr Odabasi's comment on Mr Haciski's contribution, who cited the difficulties of numerical modelling, the approach Dr Odabasi is himself pursuing suffers from just the same problem, i.e. the proper estimation of the coefficients. The only difference I can see lies in the numerical handling of the motion equations which again is not a problem of modelling.

Mr Boie, who during the late 1950s and early 1960s was closely associated with the work on stability then being carried out under Professor Wendel, has given us a short review of the reasons which lead to moment balancing. I would like to underline his remark that studying the dynamic behaviour of a ship in a seaway should not rely on the still water righting arm curve.

I thank Dr Baxter for expressing the current need for guidelines on stability requirements which might still include some margin for small effects not yet covered. Dr Baxter stresses the disadvantage of whatever static approach may be used, since certainly dynamic effects must also be considered. The moment balancing method advocated, however, does not require lengthy calculations. Righting arms at the crest and trough of a wave of ship length can be calculated quickly during the design stages even without a computer program, as well as the heeling moments.

With regard to Mr Huther's question on analog computing instead of time step methods, it is true that analog computers are ideally suited for time domain simulation. Due to time scaling, results can be obtained rapidly. However, weighing against digital computers, there are some difficulties to be overcome. After scaling the equations with respect to the voltage range of the analog components, one has to ensure accuracy of the analog circuitry. Furthermore, a digital steering system will be useful for potentiometer settings and the calculation and evaluation procedures. Even if a modern high accuracy (at least 0·1%) hybrid system is used, there still remains the problem of program availability. Some plugging of cables and scale settings are also required. Perhaps I might cite my 1969 paper on analog simulation of a nonlinear system under random parametric excitation (11).

Mr Huther's further question on the effect of transient motions upon capsizing in irregular seas is interesting. In order to lessen the impact of transients, usually ramp functions consisting of a steady increase from zero to full excitation amplitude have been applied. I think this problem also requires further attention for model tests in random seas.

Regarding small scale model similarity and roll damping, we have been acutely aware of this problem in planning open water experiments. Thus roll decay tests in still water were made in order to properly adjust at least the linear damping.

Professor Kostilainen draws attention to the problem of ships in shallow and narrow waters, which is particularly important for small ships. Although collecting accident data is quite useful, I do not think we should rely entirely on casualty statistics, but rather go further with our studies especially for new ship types. As for the human aspect in ship handling, I think the ship master needs more information from motion dynamics theory.

I completely agree with the view expressed by Dr Morrall on selecting simplified ship motion models in order to develop stability criteria. For comparison of results and judgement of new ship designs, such models could be set up immediately, although they might require further adjustment.

Many years ago, when establishing stability requirements for the Navy, we found that a ship in a following seaway hit by beam wind was a possibly severe situation. Rapid changes in wind direction are possible when passing through the eye of a hurricane or a low pressure centre. A seaway of high energy content does not change direction as suddenly as the wind.

The ABS balancing of righting arms with wind heeling for semi-submersibles is based on the assumption of dynamical wind impact. However, this is rarely found in reality in spite of the large size of most ships and structures. This may be the reason that the excess area of the uprighting moment is now to be 1·3 for semi-submersibles compared to the value of 1·4 first assumed for ships. Ships have to withstand other influences too, such as righting arm variation in a seaway or heel during turning, which are not all calculated when applying just the one quasistatic wind criterion. A less rigid criterion with respect to the choice of moments according to anticipated real conditions would be preferable.

From a private discussion I have learned that Professor Grim of Hamburg University, who was not able to attend the Conference, objects to my suggested approach on the natural frequencies in a random seaway, since in practice there will not be enough encounter periods elapsing for the ship in a following sea to reach a limit state for any discrete exciting frequency. Furthermore, each calculated natural frequency is related to just one single righting arm curve, which is quasistatic for only a small time increment and will be followed rapidly by the next one.

Certainly Professor Grim is correct, but the question remains as to whether my suggested approach might furnish a way of estimating the probability distribution of natural frequency variations in a simple manner. Comparisons from open water model tests have been encouraging(17,57).

Dr W. Abicht: Dr Kupras points out that more attention should be paid to the influence of the hull construction on the distribution of damage dimensions. This problem was also discussed before the new equivalent subdivision rules for passenger ships were established. For instance, an attempt was made to find out whether there is a significant difference between the mean damage length of single-deck vessels and ships with more than one deck (W. Riepe, HANSA, Vol. 103, No. 18, 1966). The result was that the mean damage length depends primarily on the ship's length and not on the number of decks. Obviously, the hull structure must be strengthened considerably in order to reduce the extent of damage. In a contribution to Paper No. 13 Dr Lettnin mentions special protection structures which were developed by GKSS for nuclear propelled merchant ships. In model tests these structures proved to be very effective. Of course, if these research findings are also applied to conventional ships a reduction of the damage dimensions is to be expected. For ships of normal construction, however, the distribution functions derived from damage statistics can be used. Considering the great number of different types of passenger ships, it may be true that the 'Attained Subdivision Index'—calculated according to the new subdivision rules—may not always be quite identical with the actual survival probability. But such possible inaccuracies were accepted by the working group which formulated the rules; and for just this reason it was decided to use the term 'Subdivision Index' instead of the term 'survival probability'.

In comparison with passenger ships the evaluation of tanker sub-division is less problematic because tankers do not differ much in their construction. At any rate, there is more justification for using the same distribution functions and probability diagrams for all tankers than for all passenger ships.

The author is glad to note that Mr Bird, who is a recognised expert in the field of subdivision and stability, shares the author's view that pollution avoidance regulations based on probability theory would be more effective. This view is confirmed by the Japanese IMCO paper mentioned by Mr Bird and which was unknown to the author. At that time, however, the probabilistic method was not fully developed. The effect of a double bottom or a double skin could not yet be correctly evaluated. Perhaps that proposal was made too early and therefore met with no approval.

The author apologises for the briefness of his presentation and therefore understands Mr McCallum's absolute misinterpretation of the results. Comprehension of Fig. 10 requires that Sections 2.2 and 2.3 are studied thoroughly. In addition to this, it will be helpful to read Refs. 24 and 28. It should always be borne in mind that side and bottom damages are random events. Before entering into probability calculations, for each tank and for each group of adjacent tanks or compartments, the location and dimensions of all possible damages must be determined which may cause an in- or outflow limited to the space in question. In a graphical representation (damage length y versus damage location x) these damages lie within a triangular or rhomboidal area. If such diagrams are drawn for the double-bottom tanker of Fig. 10 we obtain two different graphs: one graph for side damages (Fig. 16) and one graph for bottom damages (Fig. 17). The corresponding graphs for the double-skin tanker are presented in Fig. 18 and Fig. 19.

The actual amount of oil outflow depends on the location and size of the damage. All damages which are represented by points lying within the same triangle or rhomboid have the same pollution effect. Therefore, the amount of oil outflow can be written into each single area. Of course, not every damage will cause an oil outflow. For instance, a discharge of cargo oil does not occur if damage is limited to the engine room or the fore peak. The areas which are associated with such spaces must then be marked by the number zero. In our example this applies to the bottom triangles at the left and at the right hand sides of the diagram. The other bottom triangles cover all possible damages by which one of the three cargo tanks will be opened. Accordingly, the inserted numbers are equal to the capacity of each single tank (560 m^3). Every point lying in one of the rhomboids above the bottom triangles signifies that adjacent compartments will be damaged. According to whether one, two, or three of the adjacent compartments are cargo tanks, the numbers to be written into the rhomboids are 560, 1120, and 1680. These values must be reduced if after damage the tank or tank group will not empty completely.

The probability that the characteristics of the damage are such that its coordinates fall into a given triangular or rhomboidal area can be evaluated by using the probability diagrams (Fig. 6 for side damages and Fig. 8 for bottom damages). Details of the probability calculations are given in Tables I to IV. Thus, for every triangle and every rhomboid a probability value is obtained which, as for the amount of oil outflow, can be written into its respective area (see the lower diagrams of Figs. 16 to 19). Of course, when regarding the double-bottom tanker in the case of bottom damage or the double-skin tanker in the case of side damage, one has to consider that only those damages are of interest which pierce the inner bottom or the inner skin. Accordingly, the probability values in Fig. 17 are less than in Fig. 19 and in Fig. 18 less than in Fig. 16. The probability values which are obtained for the upper rhomboids in the diagrams are equal to zero. The reason for this is that—according to the damage statistics—almost all damages are relatively short in length. Practically, it can be assumed that no damages occur having a damage length which is greater than the following values: $y_{max} = 0{\cdot}2\ L$ (side damages) and $y_{max} = 0{\cdot}5\ x$ (bottom damages).

In Tables I to IV the manner in which the proposed standards for evaluating the effectiveness of tanker subdivision are calculated is shown. The results correspond with the values given in Fig. 10. I hope that these supplementary explanations will answer all the questions asked by Mr McCallum.

The probability of accidental oil pollution is the same in both cases :

$$P_{p2} = 0{\cdot}6160 + 0{\cdot}3130 + 0{\cdot}0055 = \underline{0{\cdot}9345}$$

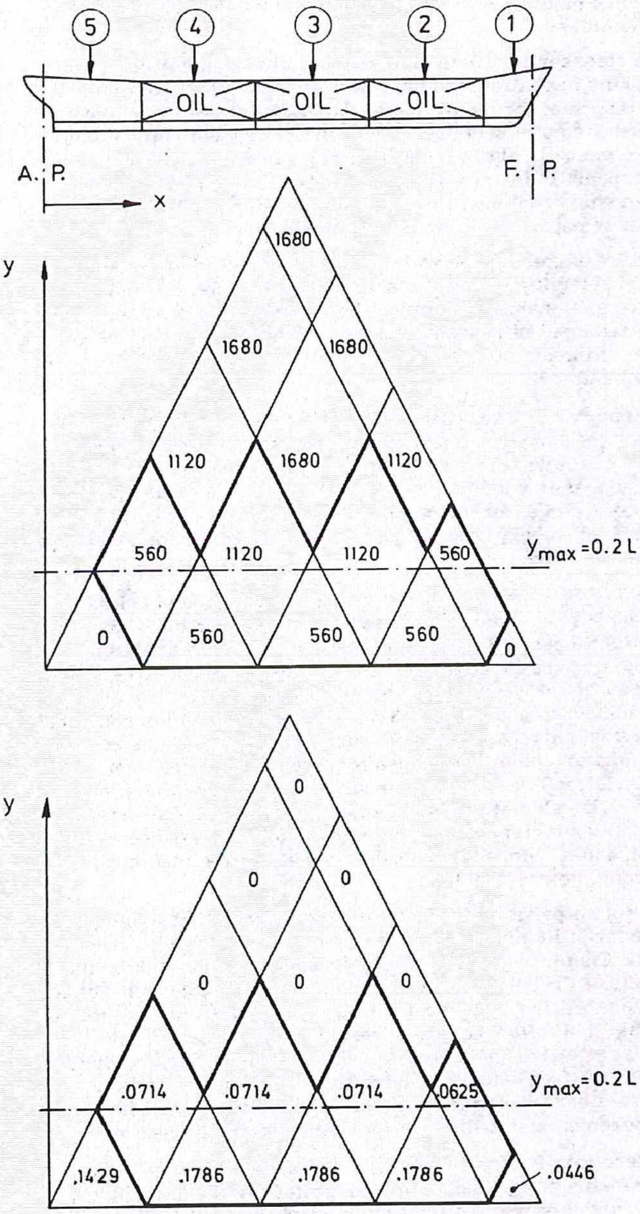

Fig. 16 Amount of Oil Outflow in m³ (top triangle) and Respective Probability Values (lower triangle) for a Double-Bottom Tanker with Side Damage

TABLE I: Double-Bottom Tanker; Side Damage Occurrence (Fig. 16)

Compartment	ℓ/L	P (any t)
1	0·1000	0·0446
2	0·2333	0·1786
3	0·2333	0·1786
4	0·2333	0·1786
5	0·2000	0·1429
1 or 2	0·3333	0·2857
2 or 3	0·4667	0·4286
3 or 4	0·4667	0·4286
4 or 5	0·4333	0·3929
1 & 2	–	0·0625(1)
2 & 3	–	0·0714(2)
3 & 4	–	0·0714(3)
4 & 5	–	0·0714(4)

(1) 0·0625 = 0·2857 – 0·0446 – 0·1786
(2) 0·0714 = 0·4286 – 0·1786 – 0·1786
(3) 0·0714 = 0·4286 – 0·1786 – 0·1786
(4) 0·0714 = 0·3929 – 0·1786 – 0·1429

Assumption: The oil in each of the cargo tanks flows out completely if the tank is breached by side damage.

Amount of oil outflow	Probability P
560 m³	0·6697 (= 0·1786+0·1786+0·1786+0·0625+0·0714)
1120 m³	0·1428 (= 0·0714 + 0·0714)
1680 m³	0

Average quantity of oil outflow

$$\overline{V}_1 = 0{\cdot}6697\times 560\ m^3 + 0{\cdot}1428\times 1120\ m^3 = \underline{535\ m^3}$$

Probability of accidental oil pollution

$$P_{p1} = 0{\cdot}6697 + 0{\cdot}1428 = \underline{0{\cdot}8125}$$

TABLE II. Double-Bottom Tanker; Bottom Damage Occurrence (Fig. 17)

Compartment	x_1/L	ℓ/L	P (any z)	P ($z < h$)	P ($z > h$)
1	1	0·1000	0·0541	0·0365	0·0176
2	0·9000	0·2333	0·2200	0·1260	0·0940
3	0·6667	0·2333	0·1410	0·0825	0·0585
4	0·4333	0·2333	0·0655	0·0397	0·0258
5	0·2000	0·2000	0·0080	0·0053	0·0027
1 or 2	1	0·3333	0·4570	0·2378	0·2192
2 or 3	0·9000	0·4667	0·5670	0·2978	0·2692
3 or 4	0·6667	0·4667	0·2810	0·1545	0·1265
4 or 5	0·4333	0·4333	0·0801	0·0496	0·0305
1 or 2 or 3	1	0·5667	0·8365	0·4330	0·4035
2 or 3 or 4	0·9000	0·7000	0·7125	0·3750	0·3375
1 & 2	—	—	0·1829(1)	0·0753(7)	0·1076
2 & 3	—	—	0·2060(2)	0·0893(8)	0·1167
3 & 4	—	—	0·0745(3)	0·0323(9)	0·0422
4 & 5	—	—	0·0066(4)	0·0046(10)	0·0020
1 & 2 & 3	—	—	0·0325(5)	0·0234(11)	0·0091
2 & 3 & 4	—	—	0·0055(6)	0·0052(12)	0·0003

(1)0·1829 = 0·4570–0·0541–0·2200
(2)0·2060 = 0·5670–0·2200–0·1410
(3)0·0745 = 0·2810–0·1410–0·0655
(4)0·0066 = 0·0801–0·0655–0·0080
(5)0·0325 = 0·8365–0·5670–0·1829–0·0541
(6)0·0055 = 0·7125–0·2810–0·2060–0·2200
(7)0·0753 = 0·2378–0·0365–0·1260
(8)0·0893 = 0·2978–0·1260–0·0825
(9)0·0323 = 0·1545–0·0825–0·0397
(10)0·0046 = 0·0496–0·0397–0·0053
(11)0·0234 = 0·4330–0·2978–0·0753–0·0365
(12)0·0052 = 0·3750–0·1545–0·0893–0·1260

First assumption: One third of the oil in each of the cargo tanks flows out if the tank is breached by bottom damage

Amount of oil outflow	Probability P
187 m^3	0·2879 (= 0·0940 +0·0585+0·0258+0·1076 +0·0020)
373 m^3	0·1680 (= 0·1167+0·0422+0·0091)
560 m^3	0·0003

Average quantity of oil outflow

$$\overline{V}_2 = 0{\cdot}2879\times 187\ m^3 + 0{\cdot}1680\times 373\ m^3 + 0{\cdot}0003\times 560\ m^3 = \underline{117\ m^3}$$

Second assumption: The oil in each of the cargo tanks flows out completely if the tank is breached by bottom damage

Amount of oil outflow	Probability P
560 m^3	0·2879
1120 m^3	0·1680
1680 m^3	0·0003

Average quantity of oil outflow

$$\overline{V}_2 = 0{\cdot}2879\times 560\ m^3 + 0{\cdot}1680\times 1120\ m^3 + 0{\cdot}0003\times 1680\ m^3 = \underline{350\ m^3}$$

The probability of accidental oil pollution is the same in both cases:

$$P_{p2} = 0{\cdot}2879 + 0{\cdot}1680 + 0{\cdot}0003 = \underline{0{\cdot}4562}$$

TABLE III. Double-Skin Tanker; Side Damage Occurrence (Fig. 18)

Compartment	ℓ/L	P (any t)*	P (t < b)	P (t > b)
1	0·1000	0·0446	0·0205	0·0241
2	0·2333	0·1786	0·0618	0·1168
3	0·2333	0·1786	0·0618	0·1168
4	0·2333	0·1786	0·0618	0·1168
5	0·2000	0·1429	0·0512	0·0917
1 or 2	0·3333	0·2857	0·0938	0·1919
2 or 3	0·4667	0·4286	0·1364	0·2922
3 or 4	0·4667	0·4286	0·1364	0·2922
4 or 5	0·4333	0·3929	0·1258	0·2671
1 & 2	–	0·0625	0·0115(1)	0·0510
2 & 3	–	0·0714	0·0128(2)	0·0586
3 & 4	–	0·0714	0·0128(3)	0·0586
4 & 5	–	0·0714	0·0128(4)	0·0586

* The P-values in this column are the same as in Table I

(1) 0·0115 = 0·0938 – 0·0205 – 0·0618
(2) 0·0128 = 0·1364 – 0·0618 – 0·0618
(3) 0·0128 = 0·1364 – 0·0618 – 0·0618
(4) 0·0128 = 0·1258 – 0·0618 – 0·0512

Assumption: The oil in each of the cargo tanks flows out completely if the tank is breached by side damage

Amount of oil outflow	Probability P
560 m³	0·4600 (= 0·1168 + 0·1168 + 0·1168+ 0·0510 + 0·0586)
1120 m³	0·1172 (= 0·0586 + 0·0586)
1680 m³	0

Average quantity of oil outflow

$$\overline{V}_1 = 0{\cdot}4600 \times 560\ \mathrm{m}^3 + 0{\cdot}1172 \times 1120\ \mathrm{m}^3 = \underline{389\ \mathrm{m}^3}$$

Probability of accidental oil pollution

$$P_{p1} = 0{\cdot}4600 + 0{\cdot}1172 = \underline{0{\cdot}5772}$$

TABLE IV: Double-Skin Tanker; Bottom Damage Occurrence (Fig. 19)

Compartment	x_1/L	ℓ/L	P (any z)*
1	1	0·1000	0·0541
2	0·9000	0·2333	0·2200
3	0·6667	0·2333	0·1410
4	0·4333	0·2333	0·0655
5	0·2000	0·2000	0·0080
1 or 2	1	0·3333	0·4570
2 or 3	0·9000	0·4667	0·5670
3 or 4	0·6667	0·4667	0·2810
4 or 5	0·4333	0·4333	0·0801
1 or 2 or 3	1	0·5667	0·8365
2 or 3 or 4	0·9000	0·7000	0·7125
1 & 2	–	–	0·1829
2 & 3	–	–	0·2060
3 & 4	–	–	0·0745
4 & 5	–	–	0·0066
1 & 2 & 3	–	–	0·0325
2 & 3 & 4	–	–	0·0055

*The P-values in this column are the same as in Table II

First assumption: One third of the oil in each of the cargo tanks flows out if the tank is breached by bottom damage

Amount of oil outflow	Probability P
187 m³	0·6160 (= 0·2200 + 0·1410 + 0·0655 + 0·1829 + 0·0066)
373 m³	0·3130 (= 0·2060 + 0·0745 + 0·0325)
560 m³	0·0055

Average quantity of oil outflow

$$\overline{V}_2 = 0{\cdot}6160 \times 187\ \mathrm{m}^3 + 0{\cdot}3130 \times 373\ \mathrm{m}^3 + 0{\cdot}0055 \times 560\ \mathrm{m}^3 = \underline{235\ \mathrm{m}^3}$$

Second assumption: The oil in each of the cargo tanks flows out completely if the tank is breached by bottom damage

Amount of oil outflow	Probability P
560 m³	0·6160
1120 m³	0·3130
1680 m³	0·0055

Average quantity of oil outflow

$$\overline{V}_2 = 0{\cdot}6160 \times 560\ \mathrm{m}^3 + 0{\cdot}3130 \times 1120\ \mathrm{m}^3 + 0{\cdot}0055 \times 1680\ \mathrm{m}^3 = \underline{705\mathrm{m}^3}$$

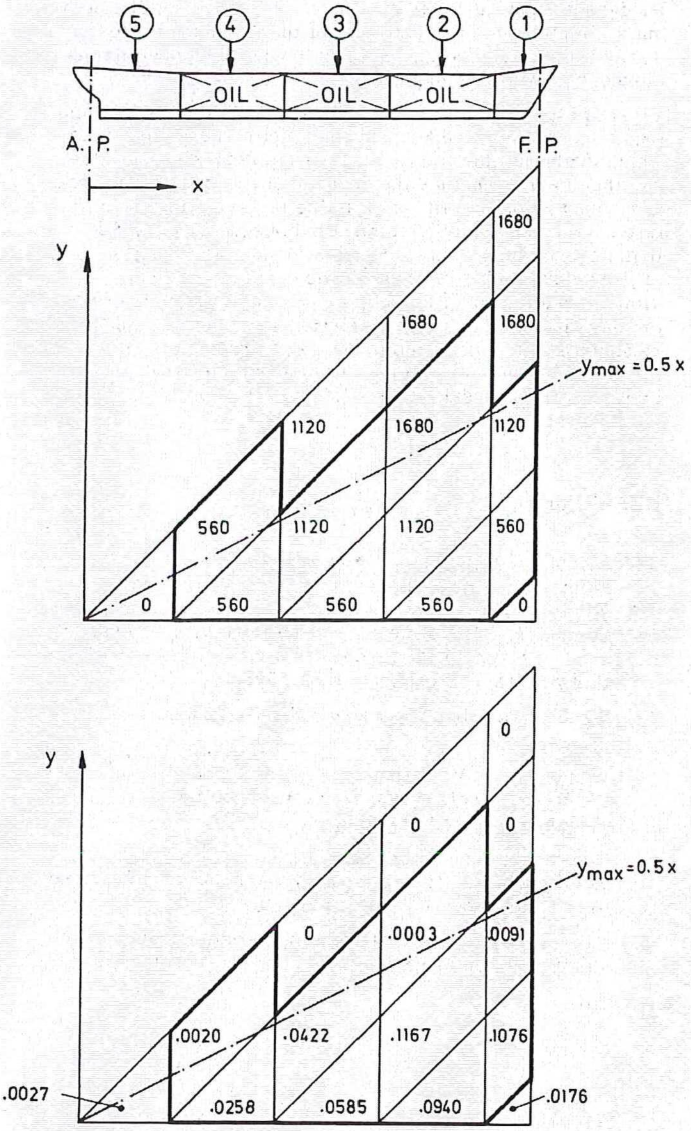

Fig. 17. Amount of Maximum Oil Outflow in m³ (top triangle) and Respective Probability Values (lower triangle) for a Double-Bottom Tanker with Bottom Damage

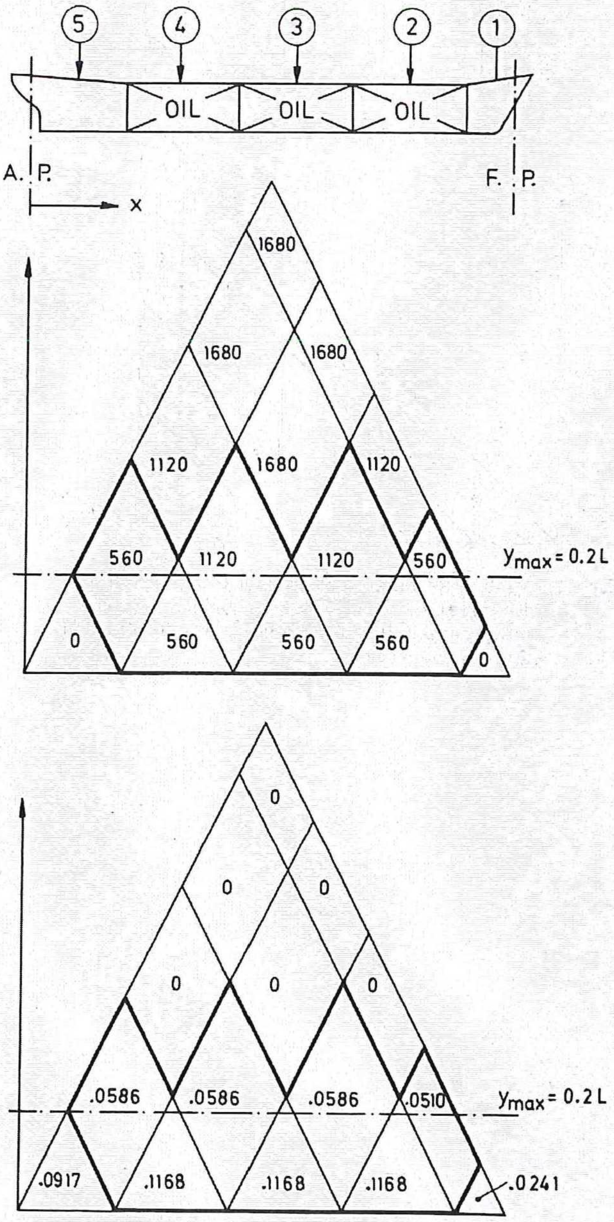

Fig. 18. Amount of Oil Outflow in m³ (top triangle) and Respective Probability Values (lower triangle) for a Double-Skin Tanker with Side Damage

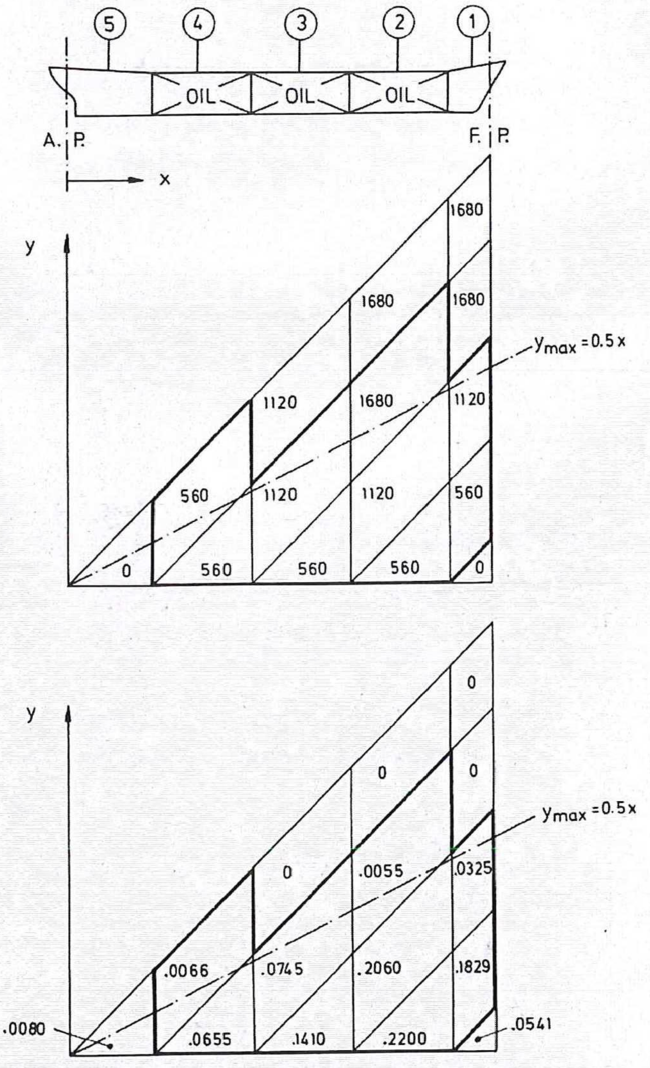

Fig. 19. Amount of Maximum Oil Outflow in m^3 (top triangle) and Respective Probability Values (lower triangle) for a Double-Skin Tanker with Bottom Damage

Professor K. Wendel: My note on freeboard is nothing else but a simple and rough estimate of the pressure forces of waves which strike a person or an obstacle on deck (front bulkheads, coamings, containers).

First of all we have to study and gain some theoretical and experimental knowledge about the kinetic energy of waves which overrun a hindrance, e.g. a pontoon or a vessel. We can then decide whether the S-shape of the freeboard curve is necessary only to fit the practice of navigation from the late century until today (as Mr Bird suspects), or whether it is nevertheless of physical significance as an expression of very careful observations of the dangers caused by violent weather conditions. If we become conscious of that primary problem and find a solution we could and should expand the calculations up to waves of different lengths, heights and directions and also pay attention to the ship speed. Such proposals were made by Mr McCallum and Dr Odabasi.

REFERENCES

52. Abicht, W., and Kastner, S.: 'Zum Untergang des Fährschiffes HERAKLION'. IfS-Schrift No. 2193, Hamburg 1972.

53. Numata, E., Michel, W. H., and McLure, A. C.: 'Assessment of Stability Requirements for Semisubmersible Units'. Trans. SNAME, Vol. 84, 1976.

54. Wendel, K.: 'Sicherheit gegen Kentern'. VDI-Z 100, No. 32, 1958.

55. Wendel, K.: 'Safety from Capsizing'. Fishing Boats of the World 2, edited by J. O. Traung, published by Fishing News Ltd., London, 1960.

56. Von den Steinen: 'Über die Zeitintegrale ungedämpfter Schiffsschwingungen bei parabolischer Auftriebskurve'. Werft, Reederei und Hafen 1934, p. 115.

57. Kastner, S.: 'Modellversuche zur Kentersicherheit in der Bucht von San Franzisko'. Hansa, Vol. 111, 1974.