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# PROBABILITY OF CAPSIZING IN STEEP AND HIGH WAVES FROM THE SIDE IN OPEN SEA AND COASTAL WATERS

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**Abstract**—A model for estimating the probability of capsize in steep and high waves from the side in open sea and coastal waters is presented. The model combines results from deterministic, single-wave model experiments and the estimation of probability of occurrence of steep and high waves for given sea states. Historical capsize frequencies for fishing and cargo vessels from Norwegian waters have been compared with the model results showing reasonable agreement.

## 1. INTRODUCTION

A MODEL for estimating the probability of capsize in steep and high waves from the side is presented. The first main element of the model is the estimation of probability of occurrence of steep and high waves for given sea states by using the joint probability density distribution of crest front steepness and wave height in deep water.

The ability of a vessel to survive such waves is found by deterministic, single-wave model experiments, varying the stability in a systematic manner. This is the second main element. Also, the operations of the vessel have to be investigated in order to assess when it is exposed to the waves, and its loading conditions and associated stability.

Finally, the human element with regard to maintaining the stability, i.e. closing openings and securing cargo, should be assessed.

Historical capsize frequencies for fishing and cargo vessels from Norwegian waters have been compared with the results from the model. The results are in reasonable agreement.

In 1981, The Norwegian Petroleum Directorate (NPD) (1981) issued its first Guidelines for safety evaluation of platform conceptual design. The NPD target value of serious accidents of $10^{-4}$ per yr has been compared with the probability of capsize. The present paper is an expansion of Dahle and Myrhaug (1986).

## 2. THE PROBABILISTIC MODEL

The definition of "capsize" is illustrated in Fig. 1. Clearly, only the "stable side position" shown in Fig. 1c may be acceptable for rescue of the crew.

A method for estimating probability of capsize was first presented by Sevastianov and is summarized in Sevastianov (1984). In the following, these principles are used in estimation of the probability of capsize, which are considered to be relevant to smaller ships only, i.e. with length below 45 m.

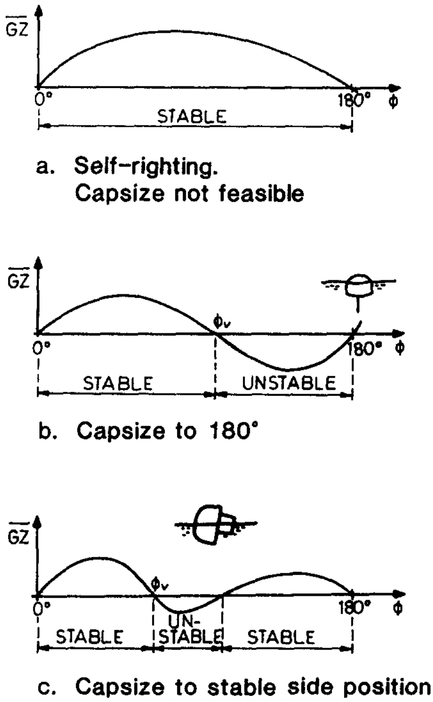


Fig. 1. Definition of capsize.

The probabilities of the different elements of capsize are dealt with in succession. First, the joint probability of encountering a steep and high wave in a given sea state is covered, and the probability of capsize after such an encounter is discussed. Then, estimates of probabilities of adherence to operational requirements, based on knowledge of the ship and its crew, have to be included as discussed by Dahle and Nedrelid (1986).

Finally, the total probability of capsize is calculated, and compared with historical data from Norwegian waters, including data from 1987.

## 3. PROBABILITY OF EXPOSURE TO BAD WEATHER

By investigating the operations of a ship, the period of time for which it is exposed can be determined. Assuming near correspondence between wind and wave direction, knowing the course of the vessel, and defining an exposed sector of 90 degrees width on each side of the ship, a probability of wave exposure can be arrived at.

For Norwegian waters, wind direction data are given by Håland (1978).

Based on a critical height $H_c$ of a near-breaking wave, the level of "bad weather" must be defined. A natural choice will be the significant wave height $H_s$. The choice depends on vessel size. $H_s \geq 1.5$ m is chosen for the sample calculation. This choice is based upon an approximate maximum critical wave height of 3 m, compared with a one-tier vessel with moderate freeboard to obtain a reasonable correspondence between ship and breaking wave geometry, see Dahle and Kjærland (1980).

The joint probability distribution of significant wave height $H_s$ and mean zero-crossing period $T_z$ for $H_s \geq 1.5$ m is given in Table 1, which is obtained from the joint frequency

TABLE 1. JOINT DISTRIBUTION OF $H_s$ AND $T_z$*

| $T_z$(s) $H_s$(m) | 3–4 | 4–5 | 5–6 | 6–7 | 7–8 | 8–9 | 9–10 | 10–11 |
|---|---|---|---|---|---|---|---|---|
| 1.5–2.5 | 0.0054 | 0.0963 | 0.1315 | 0.0738 | 0.0277 | 0.0081 | 0.0015 | 0 |
| 2.5–3.5 | | 0.0015 | 0.0508 | 0.0612 | 0.0311 | 0.0106 | 0.0022 | 0.0003 |
| 3.5–4.5 | | | 0.0017 | 0.0325 | 0.0273 | 0.0085 | 0.0015 | 0.0001 |
| 4.5–5.5 | | | | 0.0047 | 0.0206 | 0.0078 | 0.0013 | 0.0001 |
| 5.5–6.5 | | | | | 0.0066 | 0.0092 | 0.0015 | 0.0002 |
| 6.5–7.5 | | | | | 0.0005 | 0.0039 | 0.0019 | 0.0001 |
| 7.5–8.5 | | | | | | 0.0010 | 0.0018 | 0.0001 |
| 8.5–9.5 | | | | | | | 0.0007 | 0.0002 |
| > 9.5 | | | | | | | | 0.0004 |

* Based on data from Krogstad (1985).

table of $H_s$ and $T_z$ taken from Krogstad (1985). This data is from the Halten area.

Finally, the duration of various sea states is given in Kjeldsen (1981). For the Halten area the average duration of storms for winter conditions $\bar{\tau}(H_s)$, can be approximated by

$$\bar{\tau}(H_s) = 164 \cdot H_s^{-1.87}\,(\text{hr}). \tag{1}$$

From this data, a weight function $w$ is set to 1.0 if the duration of the exposed period ($t$) is exceeding the duration of the sea state. Otherwise, $w$ is taken as the ratio $t/\bar{\tau}$.

Then the general expression for the probability of being in a situation $S_i$ during a one-year operation of the ship is:

$$P(S_i) = \sum_j \sum_k P_{1jk} \cdot P_{2jk} \cdot w_{jk} \cdot P_{3jk} \cdot P_{4jk} \tag{2}$$

where $j$ and $k$ denote summing over significant wave height and zero-crossing period, respectively. Further

$P_{1jk}$ = probability of dangerous wave direction

$P_{2jk}$ = yearly fraction of time of exposure in sea state $jk$.

$P_{3jk}$ = $P(\epsilon_c, H_c \mid H_{sj}, T_{zk})$, i.e. the conditional probability of steep ($\epsilon \geqslant \epsilon_c$) and high ($H \geqslant H_c$) waves for a given sea state ($H_{sj}$, $T_{zk}$), see Section 4.

$P_{4jk}$ = joint probability of $H_s$, $T_z$, see Section 4.

The probability of capsize caused by a steep near-breaking wave in deep water is then

$$P_c = P(S_i) \cdot P_5 \cdot P_6 \cdot P_7 \tag{3}$$

where

$P_5$ = probability of being hit by a steep near-breaking wave during the period of rolling when the vessel is most exposed. In this analysis, $P_5$ = 0.5.

$P_6$ = conditional probability of capsize, given an extreme wave situation. According to the discussion in Section 5, $P_6$ is 0 for the "safe" regions of Fig. 3, and 1.0 for "unsafe" regions.

$P_7$ = conditional probability of compliance with the requirements that makes a ship "safe", i.e. the probability of important openings being closed properly, and cargo secured to sustain large heeling angles in the situations under study.

## 4. PREDICTION OF OCCURRENCES OF STEEP AND HIGH WAVES

### 4.1. *Joint distribution of crest front steepness and wave height in deep waters*

A method for estimating encounter probabilities of occurrence of steep and high waves in deep water for given sea states will be described in this section. The method is based on the idea given in Kjeldsen and Myrhaug (1978) utilizing the advantages that are contained in a zero-downcross analysis by using the wave trough and the following wave crest in the definition of a single wave, and defining the wave height as the difference between these water levels, (Fig. 2). The zero-downcross analysis provides parameters that give a representation of the physical conditions with relevance to breaking waves, and thus, parameters which should be correlated with measurements of severe ship response or wave forces in such waves. Further, a more accurate description of steepness and asymmetry in transient near-breaking waves was obtained by Kjeldsen and Myrhaug (1978), when the three following parameters were introduced: crest front steepness $\epsilon$, vertical asymmetry factor $\lambda$ and horizontal asymmetry factor $\mu$. The crest front steepness is defined by

$$\epsilon = \frac{\eta'}{(g/2\pi)\, TT'} \tag{4}$$

where $\eta'$ is the crest elevation measured from the mean water level, $T'$ the time defining the position of the wave crest relative to the zero-upcrossing point in the time domain, $T$ the zero-downcross period and $g$ the acceleration of gravity. The definitions in the time domain, also of $\lambda$ and $\mu$, are shown in Fig. 2. It is generally accepted that use of the crest elevation for design applications provides a basic parameter more relevant to finite amplitude wave geometry than the wave height. For example, for a fixed structure the position of the platform deck will be determined by the height of the wave crest above the still water level. Observations of breaking waves show that these waves can be characterized by a very steep crest front and high asymmetry factors. The $\epsilon$-parameter

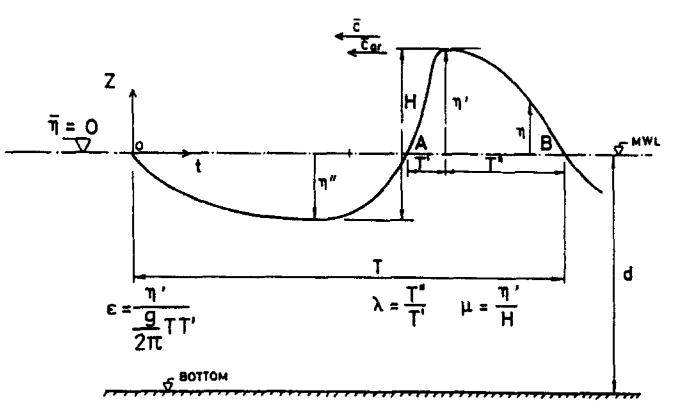


Fig. 2. Basic definitions for asymmetric waves of finite height (from Kjeldsen and Myrhaug, 1978).

is thus a mean crest front inclination in the time domain. The crest front steepness is thus a measure of the slope of the wave crest. High values of the crest front steepness can therefore be associated with large velocities and accelerations which can lead to high slam forces on structures. Capsizing of small objects on the sea surface is another relevant problem where this parameter should be useful.

However, it is not sufficient to describe the wave conditions by steepness and asymmetry parameters alone, but they should be combined with the wave height to give a better description of the severeness of a given sea state. Joint density distributions for $\epsilon$, $H$ and $\lambda$, $H$ are given in Myrhaug and Kjeldsen (1984). Myrhaug and Kjeldsen (1987) discuss closer the $\epsilon$-$H$ distribution.

The joint distribution of crest front steepness and wave height, $p(\epsilon, H)$, is obtained as a best fit to field data records from the Norwegian continental shelf.

### 4.2. *Estimates for probabilities of occurrence of steep and high waves for a given sea state in deep waters*

Estimates for probabilities of occurrence of steep and high waves can be calculated by using the joint distribution of $\epsilon$ and $H$. $p(\epsilon, H)$ is coupled to the sea state by the significant wave height $H_s = 4\sqrt{m_0}$ and the average zero-crossing wave period $T_z = \sqrt{m_0/m_2}$. $m_0$ and $m_2$ are the zeroth and second moment of the one-sided wave energy spectrum $S(f)$, respectively, defined by $m_n = \int_0^\infty f^n\, S(f)\, \mathrm{d}f$, $n = 0,2$, where $f$ is the frequency.

The probability of occurrence of waves with $\epsilon \geq \epsilon_c$ and $H \geq H_c$ for a given sea state is given by

$$P_3 = P[\,(\epsilon \geq \epsilon_c) \cap (H \geq H_c) \mid H_s, T_z]$$
$$= \int_{\epsilon_c}^{\infty} \int_{H_c}^{\infty} p(\epsilon, H)\mathrm{d}H\mathrm{d}\epsilon. \tag{5}$$

This is a conditional probability given a sea state. In Myrhaug and Kjeldsen (1987) the sea states are described by a family of JONSWAP spectra and by a joint frequency table of $H_s$ and $T_z$ (Table 1).

In this analysis sea states with $H_s \geq 1.5$ m will be considered. Further, for a given sea state two types of "extreme waves" are considered by the following threshold values of crest front steepness and wave height

$$\epsilon_c = 0.25 \text{ and } H_c = 4\text{ m} \tag{6a}$$

$$\epsilon_c = 0.25 \text{ and } H_c = 3\text{ m}. \tag{6b}$$

These choices of $H_c$ are in accordance with the examples discussed in Section 6. However, in a general case $H_c$ has to be given in correspondence with the stability characteristics, for instance the energy $E$ as discussed in Section 5 and indicated in Fig. 3. The critical value $\epsilon_c$ is not too well known, but current research is aiming at resolving this matter. The asymmetry factors $\lambda$ and $\mu$ are also important for a proper "extreme value" description.

$P_3$ is given in Table 2 for the sea states in Table 1.

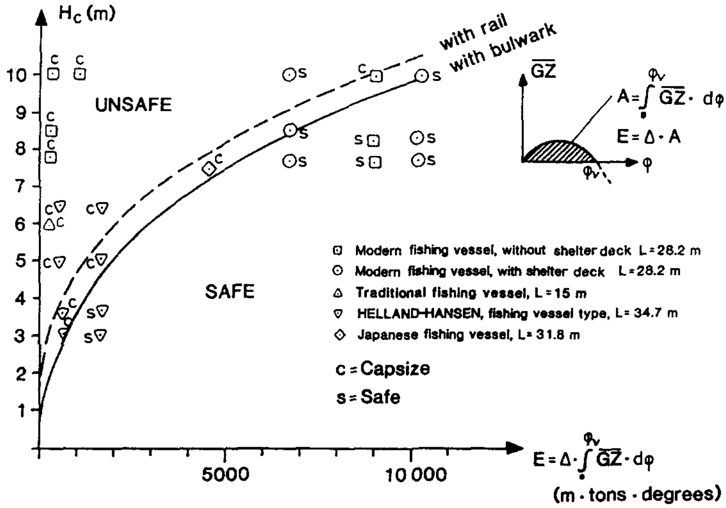


FIG. 3. Probability of capsize (from Dahle and Myrhaug, 1986). □, ⊙ Nedrelid *et al.* (1983); ▽ Dahle and Kjærland (1980); ◇ Hirayama and Yamashita (1985); △ IMO (1983).

## 4.3. *Amplification of wave steepness caused by depth-current refraction effects*

When deep water waves propagate into coastal areas several phenomena will affect how the wave conditions are changing. Among these phenomena are depth refraction, refraction due to local currents, diffraction and reflection. In this section we will limit the discussion to consider depth-current refraction effects. It is well known that plane waves approaching a straight coastline will become shorter and higher, resulting in increased wave steepness, and the waves will change direction until the wave front becomes parallel to the beach. The depth refraction also causes the convergence of wave energy over underwater ridges. In an analogous way waves propagating into an area with an opposing current will change due to current refraction effects. Generally the waves become shorter and higher, resulting in increased steepness. In many cases depth-current refraction effects will take place simultaneously and thus make the wave conditions even worse.

Kjeldsen and Myrhaug (1980) did experiments with a deep water plunging breaker in still water and with a weak steady opposing shear current, respectively. They found that the maximum value of $\epsilon$ was amplified by 13% in the presence of a weak opposing current (only 2% of the phase velocity). This example demonstrates clearly that a weak current can create significant changes in the wave dynamics.

Due to the depth-current refraction it is clear that steep and high waves may occur more frequently in exposed coastal areas than in deep water where no such effects are present. Therefore, measurements in such an exposed area should be made so that a $\epsilon$, $H$-distribution representative for the area could be established. Having access to such a distribution, the probability of occurrence of steep and high waves can be established in an analogous way to what is done above for deep waters.

TABLE 2. CONDITIONAL PROBABILITY OF "EXTREME WAVES" FOR GIVEN SEA STATES

(a) $\epsilon_c = 0.25$ and $H_c = 4$m

| $H_s$(m) \ $T_z$(s) | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| 2 | $8.1\cdot10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ |
| 3 | | $2.6\cdot10^{-3}$ | $4.2\cdot10^{-4}$ | $6.4\cdot10^{-5}$ | $1.1\cdot10^{-5}$ | $2.1\cdot10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ |
| 4 | | | $7.2\cdot10^{-3}$ | $1.9\cdot10^{-3}$ | $5.2\cdot10^{-4}$ | $1.6\cdot10^{-4}$ | $5.7\cdot10^{-5}$ | $2.2\cdot10^{-5}$ |
| 5 | | | | $1.0\cdot10^{-2}$ | $3.8\cdot10^{-3}$ | $1.5\cdot10^{-3}$ | $6.3\cdot10^{-4}$ | $2.9\cdot10^{-4}$ |
| 6 | | | | | $1.2\cdot10^{-2}$ | $5.1\cdot10^{-3}$ | $2.4\cdot10^{-3}$ | $1.2\cdot10^{-3}$ |
| 7 | | | | | $2.5\cdot10^{-2}$ | $1.2\cdot10^{-2}$ | $5.8\cdot10^{-3}$ | $3.0\cdot10^{-3}$ |
| 8 | | | | | | $2.1\cdot10^{-2}$ | $1.1\cdot10^{-2}$ | $5.9\cdot10^{-3}$ |
| 9 | | | | | | | $1.8\cdot10^{-2}$ | $9.9\cdot10^{-3}$ |
| 10 | | | | | | | | $1.5\cdot10^{-2}$ |

(b) $\epsilon_c = 0.25$ and $H_c = 3$ m

| $H_s$(m) \ $T_z$(s) | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 |
|---|---|---|---|---|---|---|---|---|
| 2 | $1.2\cdot10^{-3}$ | $1.1\cdot10^{-4}$ | $8.3\cdot10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ |
| 3 | | $1.1\cdot10^{-2}$ | $2.3\cdot10^{-3}$ | $5.2\cdot10^{-4}$ | $1.4\cdot10^{-4}$ | $4.2\cdot10^{-5}$ | $1.5\cdot10^{-5}$ | $5.4\cdot10^{-6}$ |
| 4 | | | $1.8\cdot10^{-2}$ | $5.8\cdot10^{-3}$ | $2.1\cdot10^{-3}$ | $8.4\cdot10^{-4}$ | $3.7\cdot10^{-4}$ | $1.7\cdot10^{-4}$ |
| 5 | | | | $2.0\cdot10^{-2}$ | $8.1\cdot10^{-3}$ | $3.6\cdot10^{-3}$ | $1.7\cdot10^{-3}$ | $8.7\cdot10^{-4}$ |
| 6 | | | | | $1.9\cdot10^{-2}$ | $9.0\cdot10^{-3}$ | $4.5\cdot10^{-3}$ | $2.4\cdot10^{-3}$ |
| 7 | | | | | $3.5\cdot10^{-2}$ | $1.7\cdot10^{-2}$ | $8.8\cdot10^{-3}$ | $4.8\cdot10^{-3}$ |
| 8 | | | | | | $2.8\cdot10^{-2}$ | $1.5\cdot10^{-2}$ | $8.2\cdot10^{-3}$ |
| 9 | | | | | | | $2.3\cdot10^{-2}$ | $1.3\cdot10^{-2}$ |
| 10 | | | | | | | | $1.9\cdot10^{-2}$ |

## 5. PROBABILITY OF CAPSIZE WHEN HIT BY A BREAKING WAVE FROM THE SIDE

In this section the probability of capsize when exposed to breaking waves from the side is discussed.

The problem is only relevant for smaller vessels and published work is scarce. Notably, Kholodin and Tovstikh (1969), Balitskaya (1970), Morrall (1980), Dahle and Kjærland (1980), Nedrelid *et al.* (1983), Sevastianov (1984), Hirayama and Yamashita (1985), and Hirayama and Sadakane (1986) have given some data.

In Fig. 3, where capsize and some non-capsize cases for fishing vessels are plotted, a tentative curve has been drawn. A distinction has been made between vessels with bulwark and rail. The "stability" is expressed by the internal work $E$ ideally done by the vessel until $\overline{GZ}$ becomes zero, i.e.

$$E = \Delta \int_0^{\phi_v} \overline{GZ}\, \mathrm{d}\phi \text{ (tons} \cdot \text{m} \cdot \text{degrees)} \tag{7}$$

where

$\Delta$ = displacement (tons),
$\overline{GZ}$ = righting arm (m),
$\phi_v$ = heeling angle (degrees).

$\phi_v$ should be taken as the angle where $\overline{GZ}$ physically becomes zero, and might be the flooding angle if considerable ingress of water can take place at the roll angle succeeding a breaking wave. Hydrodynamic damping is neglected.

- with corresponding $\overline{GZ}$-curves, a loaded vessel is safer than one in ballast;
- the area below the $\overline{GZ}$-curve is important, and may be provided by enclosed superstructures, by low $\overline{KG}$ or both;
- for large $\phi_v$ and reasonable $\Delta$ and $\overline{GZ}$-values, capsize is very unlikely;
- models with positive $\overline{GZ}$-values extending beyond 90 degrees never capsized in waves of $H \leqslant 10$ m.

Another important matter for cargo vessels is the behaviour of the cargo when heeled. Capsize in loaded condition is extremely rare for Norwegian fishing vessels (see Table 3).

Finally, the human aspect with regard to closing of openings of considerable size (doors, cargo hold hatches) must be considered and a probability must be assigned. This aspect may decide $\phi_v$, and therefore has an important impact on the probability of capsize. For the Norwegian fleet, it is an unfortunate fact that the crew on fishing vessels in general is less concerned with closing appliances than crew on merchant ships. This matter might be improved by introduction of simple-to-read operation manuals and better training of skippers, see Dahle and Nedrelid (1986). Also, negligence with regard to securing cargo should be considered, when relevant.

## 6. APPLICATION

### 6.1. *Historical capsize probability*

Some of the contributions to $P_c$, namely $P_2$ and $P_7$, are not well known (see Equation (3)). To arrive at estimates for these parameters an analysis of capsized vessels and

TABLE 3. DATA FOR NORWEGIAN VESSELS LOST 1970 – 1987, SEE FIG. 4

| Ref. No. | Time Month/yr | Type C=cargo F=fishing | Loading conditions L=loaded B=ballast | Circumstances C=capsized D=disappeared | Name | LOA(m) | Area O=open sea C=coastal water |
|---|---|---|---|---|---|---|---|
| 1 | 3/70 | C | L | C | Normannvik | 56 | O |
| 2 | 6/70 | F | B | D | Veiflu | 15 | O |
| 3 | 9/70 | F | B | D | Jøviktinn | 21 | O |
| 4 | 11/70 | C | L | D | O.Larsen | 38 | O |
| 5 | 1/72 | F | B | D | Seilfjell | 24 | O |
| 6 | 7/72 | F | B | D | Rossøy | 17 | O |
| 7 | 2/73 | C | L | C | Tryggen | 28 | C |
| 8 | 3/73 | C | L | D | Vatnanes | 40 | O |
| 9 | 12/73 | F | B | D | Vaarland | 15 | O |
| 10 | 10/74 | C | L | D | Øyfinn | 42 | C |
| 11 | 12/74 | C | L | D | Hardarvaag | 40 | C |
| 12 | 4/75 | C | L | C | Staalholm | 47 | C |
| 13 | 1/76 | F | B | D | Fritz-Erik | 19 | C |
| 14 | 2/76 | F | B | D | Minka | 21 | C |
| 15 | 1/77 | F | B | D | Tulipan | 22 | O |
| 16 | 1/77 | F | B | D | Emly | 18 | O |
| 17 | 2/78 | F | B | D | Utvik-Senior | 18 | C |
| 18 | 9/79 | C | L | C | Austri | 55 | C |
| 19 | 8/79 | C | L | C | Berina | 39 | C |
| 20 | 8/79 | C | L | C | Lancing I | 22 | C |
| 21 | 2/81 | F | B | D | Western | 19 | C |
| 22 | 2/81 | C | L | C | Castel | 35 | C |
| 23 | 6/81 | C | L | C | Activ | 26 | C |
| 24 | 11/81 | C | L | D | Hammerholm | 52 | O |
| 25 | 11/81 | C | L | C | Sørstrand | 52 | O |
| 26 | 1/82 | F | B | C | Fagernes | 15 | C |
| 27 | 11/82 | F | B | C | Bajan | 14 | C |
| 28 | 1/83 | F | B | C | Lyngby | 15 | C |
| 29 | 8/83 | F | B | D | Sari | 12 | C |
| 30 | 11/84 | F | L/B | C | Norddønna | 20 | C |
| 31 | 12/84 | C | L | C | Sun Coast | 40 | C |
| 32 | 1/85 | F | B | C | Werni Jr | 21 | O |
| 33 | 4/86 | F | B | C | Mehamnfisk | 19 | O |
| 34 | 1/87 | F | B | C | Anki | 30 | O |
| 35 | 2/87 | F | B | C | Skaabas | 18 | O |

vessels that have disappeared in the period 1970 – 1987 is made. The analysis covers all Norwegian vessels below 500 BRT. The result is shown in Fig. 4 and in Table 3. Further, based on typical operational profiles of the vessels, their operational periods in typical coastal waters and open sea have been estimated.

The total vessel population during the period has also been found. The main data are given in Table 4.

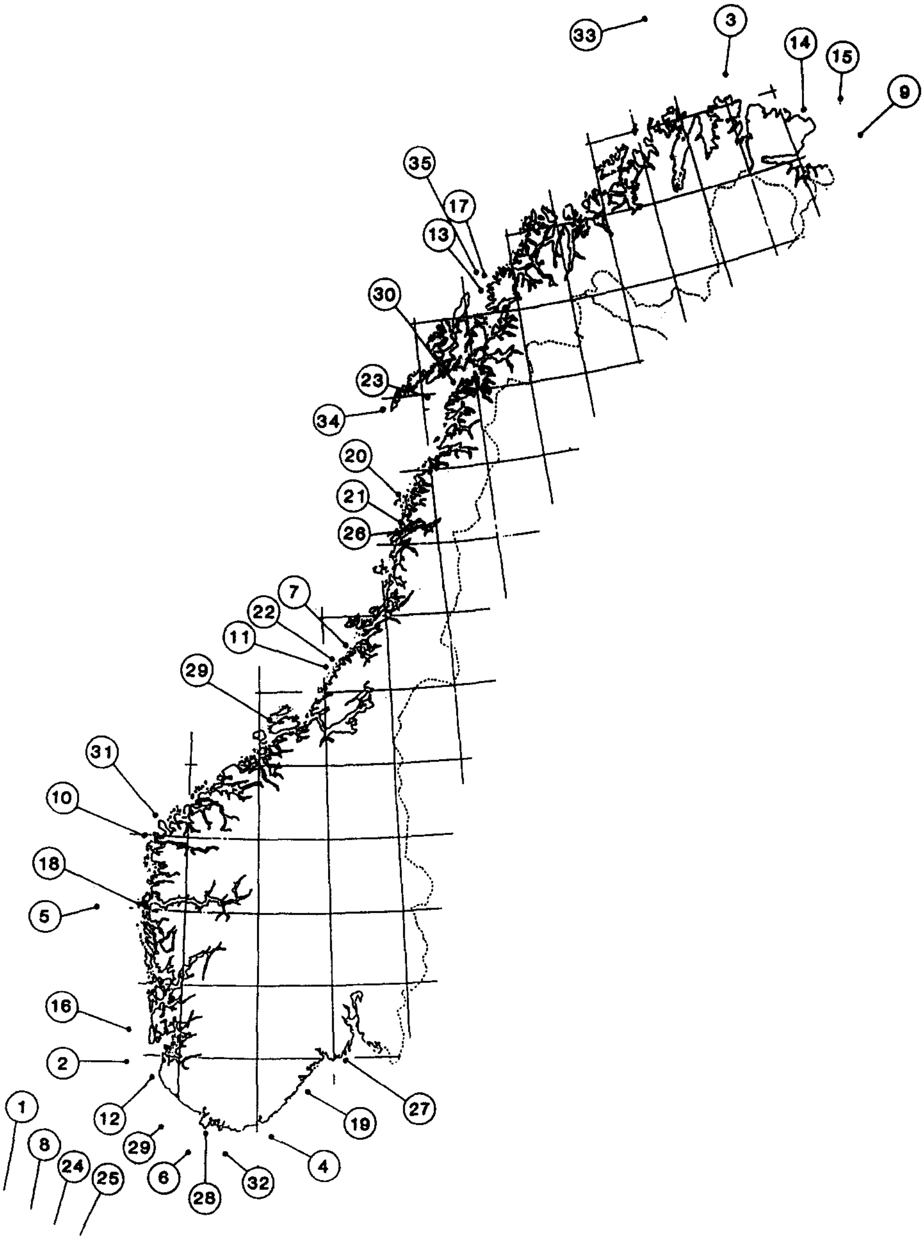


FIG. 4. Norwegian vessels below 500 BRT capsized and disappeared 1970 – 1987, see Table 3.

TABLE 4. DATA SUMMARY FOR NORWEGIAN VESSELS LOST 1970 – 1987

| | Fishing vessels | Cargo vessels |
|---|---|---|
| Coastal water | 9 | 10 |
| Open sea | 11 | 5 |
| Population | 4500 | 2400 |
| Operating in coastal water | 0.5 | 0.5 |
| Operating in open sea | 0.5 | 0.5 |

Regarding vessels that have disappeared, it has been assumed that they have capsized. The historical probability of capsize per year is then as given in Table 5. As can be seen all the probabilities are above the target value of $10^{-4}$ indicated by the Norwegian Petroleum Directorate, provided that the $\overline{GZ}$-curve have the shape shown in Fig. 1b.

Considering the capsize probability as excessive, the Norwegian Maritime Directorate issued new rules for stability of new fishing vessels in 1983, requiring the $\overline{GZ}$-curve to be positive up to a heeling angle of at least 80 degrees for new, and 60 degrees for existing vessels.

TABLE 5. HISTORICAL CAPSIZE PROBABILITY (PER YR)

| | Fishing vessels | Cargo vessels |
|---|---|---|
| Coastal water | $2.3 \cdot 10^{-4}$ | $5.2 \cdot 10^{-4}$ |
| Open sea | $2.8 \cdot 10^{-4}$ | $2.6 \cdot 10^{-4}$ |
| Total | $2.5 \cdot 10^{-4}$ | $6.3 \cdot 10^{-4}$ |

For cargo vessels requirements to the $\overline{GZ}$-curves have not been strengthened since 1969. However, much attention has been paid to lashing and safe stowage of cargo.

### 6.2. *Capsize probability according to the mathematical model*

The vessel used in this sample calculation is HELLAND-HANSEN, see Fig. 3. For the model, the various parameters can be found as follows:

$P_1$ = *probability of weather from the side*
$P_1$ = *0.5* has been used due to almost even wind distribution
$P_2$ = *yearly fraction of exposed time*
$P_2$ = 0.75 for fishing vessels
$P_2$ = 0.50 for cargo vessels
$P_3$ = *conditional probability of steep and high waves for a given sea state*
$P_3$ is given in Table 2a and 2b.
$w$ = *weight function*
For each sea state, $w$ can be calculated as $w = t/\bar{\tau}$, see Equation (1).
The result is given in Table 6.
$P_4$ = *joint probability distribution of* $H_s$ *and* $T_z$
$P_4$ is given in Table 1.

TABLE 6. WEIGHT FUNCTION $w$ VS $H_s$

| $H_s$(m) | 1.5–2.5 | 2.5–3.5 | 3.5–4.5 | 4.5–5.5 | 5.5–6.5 | 6.5–7.5 | 7.5–8.5 | 8.5–9.5 | ≥9.5 |
|---|---|---|---|---|---|---|---|---|---|
| $w$ | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 0.5 | 0.4 | 0.3 | 0.3 |

According to Equation (2); the probability per year of being exposed to an "extreme wave" in sea states with $H_s \geq 1.5$ m is

$P(S_i)$ = $1.5 \cdot 10^{-4}$ $H \geq 4$ m, $\epsilon \geq 0.25$ for fishing vessels
$P(S_i)$ = $1.0 \cdot 10^{-4}$ $H \geq 4$ m, $\epsilon \geq 0.25$ for cargo vessels
$P(S_i)$ = $3.8 \cdot 10^{-4}$ for $H \geq 3$ m, $\epsilon \geq 0.25$ for fishing vessels
$P(S_i)$ = $2.5 \cdot 10^{-4}$ for $H \geq 3$ m, $\epsilon \geq 0.25$ for cargo vessels

$P_5$ = *probability of being hit within* T/2, *where* T *is the period of rolling*
$P_5$ = 0.5
$P_6$ = *conditional probability of capsize given an extreme wave situation*
With $\overline{GZ}$-curves corresponding to Fig. 1b or c, Fig. 3 indicates:
$P_6$ = 1 for $H \geq 4$ m, $\epsilon \geq 0.25$ for $\overline{GZ}$-values close to IMO requirements and
$P_6$ = 1 for $H \geq 3$ m, $\epsilon \geq 0.25$ $GZ$-values about $\frac{1}{2}$ of IMO requirements.
$P_7$ = *human reliability*
$P_7$ = 1 because $\phi_v$ is reached before openings are submerged. The results of the sample calculation is summarized in Table 7.

TABLE 7. $P_c = \prod_{i=1}^{7} P_i$ FROM THEORETICAL MODEL FOR SAMPLE VESSEL (PER YR)

| $H_s$(m) | 3 | 4 |
|---|---|---|
| IMO | never capsize | $1.5 \cdot 10^{-4}$ |
| $\frac{1}{2}$ IMO* | $3.8 \cdot 10^{-4}$ | always capsize if hit by the wave |

* Taken as area under $\overline{GZ}$-curve, adjusted by movement of centre of gravity.

## 7. SUMMARY AND CONCLUSIONS

The historical capsize probability of Norwegian cargo vessels is higher than for fishing vessels by a factor of about 3. The probability is higher for coastal waters than for ocean areas. Most accidents occur in loaded condition, indicating shift of cargo as contributing factor.

For fishing vessels, there is no marked difference in capsize probability between coastal and ocean areas. The ballast condition, which is most frequent, is dominating.

The sample calculation from the mathematical model clearly indicates the relation between stability and height of the near-breaking wave.

With IMO recommendations fullfilled, the probability of capsize is close to the target value of $10^{-4}$ per yr of the Norwegian Petroleum Directorate, while it is higher by a factor of 2.5 when IMO-values are halved.

Comparing the historical capsize probability with the typical sample calculation value, an indication may be that a large part of the Norwegian fishing fleet has a stability well below the IMO minimum standard. This could partly be caused by insufficient operational measures to uphold stability.

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