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Theme C

Evaluation of Collision Probabilities
Evaluation des probabilités de collision
Beurteilung der Kollisionswahrscheinlichkeit

Integrated Study on Marine Traffic Accidents

Étude intégrée des accidents de trafic maritime

Integrierte Forschung über Schiffverkehrs-Unfälle

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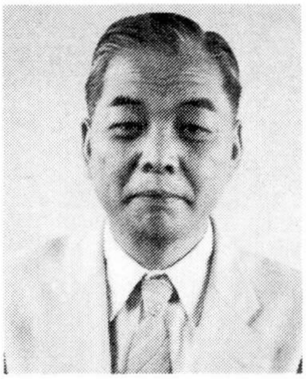

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SUMMARY
The frequency of a ship collision with a fixed object or a ship depends on the hypothetical frequency of ship collision with fixed autopilots and the probability of mismaneuver.

RÉSUMÉ
La fréquence de la collision d'un navire avec un objet fixe ou un navire est fonction de la fréquence hypothétique de la collision de navires avec pilotage automatique fixe et de la probabilité de fausse manoeuvre.

ZUSAMMENFASSUNG
Die Frequenz einer Schiffskollision mit einem festen Gegenstand oder einem Schiff ist von der hypothetischen Kollisionsfrequenz eines automatisch gesteuerten Schiffes und der Wahrscheinlichkeit falschen Manövrieren abhängig.

1. INTRODUCTION

Estimation of the number of ship collisions with bridge and offshore structure would be one of the main topics of the colloqium. Therefore, summary of marine traffic study is briefly introduced here which, author wishes, might give basis for further discussion.

2. ESTIMATION OF COLLISION FREQUENCY

2.1 Definition

Three frequencies have interested people involved in the study, namely,

(1) the number of collisions, Nc, or of ships in collision, Ns, in a certain area in a unit time,

(2) the frequency of collisions per ship in a unit time, Fs, and

(3) the frequency of collisions per trip, Ft, e.g., per port entry or per trip through a strait.

Though Fs is obtained without difficulty, Nc and Ft are more adequate for the accident analysis. The frequencies depends on the degree of damage. Therefore, the probability of degree of damage, Pr, is an important factor for the study. We should like to include all accidents even with practically no damage. However, there is a large unceruainty in the number of accident reports since exaustive record is scarcely expected. The frequencies for total loss accident may be written as NcPr(100%). Other scale for the degree of damage is also employed. For example, the Maritime Safety Agency (Japan) uses the definition, "required rescue", which is closely related with "operable".

Nc and Ft are dependent on the ship length, L, the speed, V, the density of ships, ρ, weather and many other factors. Let us try to estimate the number of collisions with traffic-related quantities.

2.2 Collision with Fixed Objects

Suppose that many ships proceed with fixed autopilots toward an fixed object as shown in Fig.1. The number of ships in collision, Nau, in a time length, T, is roughly represented as

$$Nau = \rho V D T \quad \cdots (1)$$

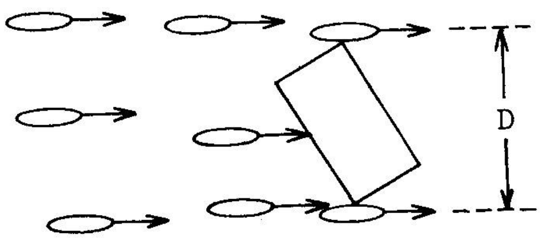

Fig. 1 Collision with fixed object

where D is the cross section and is equal to the sum of the width of ship and the width of the object looking in the direction of the velocity. When the density is uniform, following approximation is possible,

$$N_{au} = QTD/W \qquad \cdots (2)$$

where W is the width of traffic flow and Q $(= \rho WV)$ is the traffic volume.
We may rewrite Eq. (1) as

$$N_{au} = \int_0^T \int_L \int_{\vec{V}} \rho V D \Phi dL \, d\vec{V} \, dt \qquad \cdots (3)$$

where Φ is the normalized distribution function of the ship length and the velocity.
The ratio, P, of the number of collision, Nc, and Nau, is important and interesting. 16 cases of collision with drilling platforms are reported in the Akashi Channel where a large bridge is to be constructed. The average width of the traffic flow was about 4km. The total number of drilling points was 22 and the total time length that each platformwas present was 70 months $(T = 70 \times 30 \times 24$ hr). The cross section, D, of a platform including stays and guys was about 0.2 km and the traffic volume per day was 1100 $(Q = 1100/24)$. Then, Eq. (2) yields

$$P = N_c/N_{au} = 16/[(1100/24) \times (70 \times 30 \times 24) \times 0.2/4)$$
$$= 1.39/10{,}000 \fallingdotseq 10^{-3.86}$$

Similarly, Nau is easily calculated for grounding. The logarithms of the ratios, log P, thus obtained are [1]:

Uraga Strait	(Fort No.2)	−3.9,
Bisanseto	(Oseishima)	−3.5,
Akashi Channel	(Hiraiso)	−3.2,
Akashi Channel	(Sementoiso)	−3.0
and Naruto Strait	(Nakaze)	−4.0.

Above values with −3.9 for drilling platforms give

$$\log P = -3.7 \pm 0.4.$$

This indicates that the probability of mismaneuvers leading to collision to fixed object or grounding is about 2/10,000.

2.3 Collision of Ships

Nau is easily calculated in a water area where there are two groups of ships as shown in Fig. 2. The number of collisions with one of ships in the group "i" in a time length T is $\rho_j V_r D_{ij} T$ where V_r is the relative speed and D_{ij} is the cross section and hence, the number of collisions in area S is

$$\rho_i \rho_j V_r D_{ij} \, S T \qquad \cdots (4)$$

since there are $S\rho_i$ ships in the area. This formula is generalized by increasing the number of groups and employing following representation,

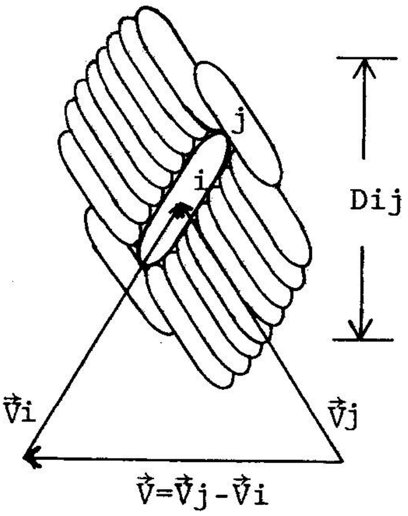

Fig.2 Collision of a ship in group "i" with ships in group "j"

$$\sum_i \sum_j \rho_i \rho_j V_r \rightarrow \int_{L_1}\int_{L_2} \iint_{\vec{V}_1} \iint_{\vec{V}_2} (\rho^2/2)\Phi_1 \Phi_2 V_r \, dL_1 dL_2 d\vec{V}_1 d\vec{V}_2,$$

where Φ_1 and Φ_2 are normalized distribution function of ship size and velocity. Since V_r vanishes for ships in the same group, $\rho^2/2$ gives cross product $(\rho_i \rho_j)$ only where $\rho(=\sum \rho_i = \sum \rho_j)$ is total density. Finally, considerably complicated expression,

$$N_{au} = \int_0^T \iint_S \int_{L_1}\int_{L_2} \iint_{\vec{V}_1} \iint_{\vec{V}_2} (\rho^2/2)\Phi_1 \Phi_2 V_r dL_1 dL_2 d\vec{V}_1 d\vec{V}_2 dS\, dt \qquad \cdots (5)$$

is obtaind.

The values of log P in three Japanese straits are[2]

$\log P = -4.1 \pm 0.2$ for codirectional encounter

and $\log P = -3.9 \pm 0.3$ for head-on encounter.

Above calculation is based on accident record from 1962 to 1968 and traffic data in those years were far from sufficient. Lewison's data[3] in Dover Strait gives -4.0 for codirectional encounter and -3.9 for head-on encounter.

Our group is performing an extensive study on log P in Japanese water for years from 1970 to 1981 and interim result in Bisanseto gives

$\log P = -4.08 \pm 0.16$ for co-directional collision,
$\log P = -4.86 \pm 0.23$ for head-on collision,
$\log P = -4.29 \pm 0.18$ for crossing collision and
$\log P = -4.44 \pm 0.43$ for collision to fishing boat at work.

These convince us that the ratio, $P\ (=N/N_{au})$, is of the order of

1/10000 either for collision of ships or collision to object.

2.4 Various Factors

2.4.1 Degree of Damage

The damage rate, x, defined here as the ratio between the estimated damage to the ship (excluding loss of cargo) and the estimated value of the vessel, depends mainly on the gross tonnage ratio, y, between the gross tonnages of two ships iovolved. The cumulative relative frequency, F(x,y), of the probability of damage over x, is[4]

$0.033\ x^{-0.60}$ for $y=10$,
$0.008\ x^{-0.63}$ for $y=1$,
$0.004\ x^{-0.90}$ for $y=0.1$
and $0.00001\ x^{-1.1}$ for $y=0.01$.

This permits, together with PNau, estimation of loss due to ship collision in a certain area. However, information on damage is deficient for collisions with objects.

2.4.2 Weather

562 collisions and 354 groundings in 6 Japanese straits from 1966 to 1971 are classified with respect to the visual range. Analysis with these data and the frequency of visual ranges indicates that P is inversely proportional to the visual range for both collision and grounding[5].

Influence of darkness on P is studied in four Japanese straits where diurnal change in the traffic volume is compensated. Result shows that Ps for collision and grounding at night are 4 times those at daytime.

2.4.3 Type and nationality

Study in several straits in Japan yields that the ratio, P of ferry or passenger boat is about 1/6 that of freighter while P of fishing boat is about 3 times larger[6]. This indicates that reduction of P to P/6 is possible by with analysis of operation of ferries and passenger boats. Difference in Ps of freighter and tanker is abut 17% and may be neglected. Lunde and others[7] show that the annual rate of total loss of vessels over 499 g.t. due to collision ranges from 1/1000 to 8/1000 and also, significant difference exists among ship groups of different nationalities. This indicates the possibility of further improvement.

3. DOMAIN AND ENCOUNTER

3.1 Domain and Bumper Model

Fujii and others[8] indicated the presence of the effective domain around a ship into which other ships avoid entering. The domain for co-directional encounter is approximately elliptic with a long radius of 8L and short radius of 3.2L under ordinary navigation condition. Behavior studies in different types of encounter gives very simple model. Ship movement is well simulated withthe elliptic bumper model as shown TYPE A in Fig. 3. Ships proceed along their route so long as their bumpers do not overlap. When overlap is anticipated, evasive action is taken to resolve the encounter situation.

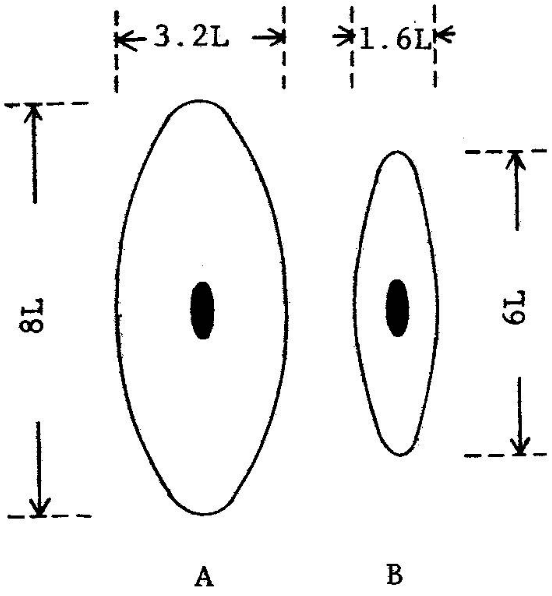

Fig.3 Size of bumper model

Since determination of bumper size requires considerably long traffic observation with high resolution radar(s), dependence of the bumper size on the speed has not been obtained.

Observation at port entrance suggests shrunk bumper shown as "B" in Fig. 3 when navigating at harbor speed.

Goodwin[9] has introduced "ship domain" which is closely related to our "effective domain" and "bumper model" in idea, but not in size. We expect observation on domains in other counuries.

3.2 Encounter and Traffic Capacity

The number of encounters, N_{en}, can be estimated from traffic related data by substituting the bumper for ship contour line in the calculation of N_{au} in the former section. Estimated values agree with observed values within a factor of $10^{\pm 0.5}$.

Therefore, we may relate three frequencies, N_c, N_{au}, and N_{en} with approximate ratio, 1/10000 : 1 : 10.

Theoretical traffic capacity of one-way route, C_{th}, is obtained as

$$C_{th} = 1.15WV/(8L \times 3.2L) \qquad \cdots(6)$$

where the bumper model A is employed and 1.15 is the close-packing factor. Okuyama[10] has studied the capacity of one-way route and route network by mathematical simulation with the bumper model.
Traffic capacity of route between bridge piers can also be estimated by such simulation. The practical capacity, often called the design capacity, is influenced by many factors which are still under study.

3.3 Multiple Encounter

The number of collisions where influence of the third ship is reported occupies a considerable part, about 6% of the total in Japan. Fujii[11] defined multiple encounter as simultaneous overlaps three or more bumper models. Mathematical analysis yields a considerably complicated formula for estimating the frequency of multiple encounters in which an index, ρE, the product of the density and the area of single overlap, plays an important role. When ρE approaches unity, the share of multiple encounter increases steeply.

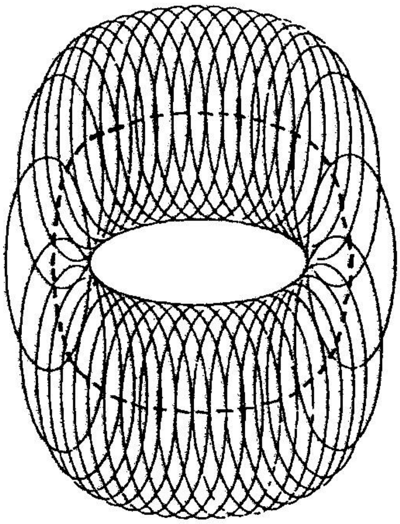

Fig.4 Area of singme overlap shown with dotted line (90° encounter)

E is a function of ship length and encounter condition and is about $90L^2$ when the ships are of a same size.
Multiple encounter, as Jensen[12] has pointed out, is a dangerous situation and should be avoided. If we admit $\rho E=1$ as the limit, the traffic capacity may decrease to about 1/4 of the theoretical capacity, C_{th}. If we regard a bridge pier as the third ship, encounters of ships in approach area to a bridge should be avoided.
There is another approach to estimate the frequency of multiple encounter. estimation of the probability of simultaneous presence of two or more ships in an effectiwe domain. This also leads to similar result.

4. CONCLUSION

The number of collisions to stationary objects or of ships is approximated with PN_{au}, where P is the probability of mismaneuver and N_{au} is the

number of collisions when ships navigate with fixed autopilots. Result of survey shows that P seems a constant close to 1/10000 under ordinary condition. This allows estimation of such such collisions in the viscinity of a bridge.
The relation of the number of encounters and the number of collisions is also studied where the bumper model seems adequate to simulate the behavior of ships and allows furtier esuimation of multiple encounters.
The author wishes information exchange on such data in differenu water of the world.

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Extreme and First-Passage Time of Ship Collision Loads

Distribution du risque maximal de collisions de navires

Verteilung des extremen Risikos bei Schiffzusammenstößen

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SUMMARY
The paper outlines a general theory from which the distribution function of the extreme peak collision load encountered during a certain intended lifetime can be calculated assuming the arrival of ship collisions to be specified by a Poisson counting process.

RÉSUMÉ
L'article esquisse une théorie générale permettant de déterminer la fonction de distribution du risque maximal de collision dans une période donnée étant supposé que les collisions de navire interviennent selon une distribution de Poisson.

ZUSAMMENFASSUNG
Der Artikel stellt eine allgemeine Theorie dar, welche die Verteilungsfunktion eines extremen Kollisionsrisikos während einer bestimmten Zeit voraussieht. Es wird vorausgesetzt, daß das Auftreten einer Schiffskollision nach einer Poissonschen Verteilung geschieht.

1. INTRODUCTION

Clearly the impact forces from collision between greater ships and bridge piers must be considered as part of the design basis of the pier [1 - 3]. Collisions are caused by a variety of events including human and mechanical errors [2]. Since almost all decisive parameters such as impact velocity magnitude and direction of wind, waves and current are uncontrolled, stochastic modelling seems to be the only natural way of modelling. This means that the feasibility of the project is decided from the reliability of the system to withstand impact loadings below a certain design load during the intended lifetime of the structure.

In this paper the reliability problem is decoupled into two minor problems concerning the distribution of impact loads on condition that collision does take place, and estimation of the probability rate, at which larger ships collide with the pier.

The distribution function of the extreme peak collision load encountered during a certain intended lifetime can be calculated assuming the arrival of ship collisions to be specified by Poisson counting processes. The equivalent first passage time problem, i.e. the distribution function of the elapsed time until a certain design impact load is exceeded for the first time, is also indicated. The *average* collision force can be estimated with known impact energy by the well-known Minorsky formula [4 - 7]. However, the average impact load is of minor interest because the *peak* value of the impact load can amount to more than double the average value, depending on strength and water filling of the bow construction [3, 8, 9].

At the present state the probability rate at which a ship will encounter the pier can only be estimated by rather costly simulation studies. It is assumed that somewhere before the passage of the bridge a decisive event, such as fixation of the rudder, machine stop, etc., takes place with a known rate of occurrence carrying the ship out of control. For specific samples of position, velocity, course of the ship at the instant of such events, and magnitude and direction of wind, waves and current the corresponding ship path can be obtained by solving the manoeuvring differential equations. The conditional collision rate can then be estimated from the relative number of realizations at which the ship will encounter the pier. It is essential to the cost of the calculation that the number of independent stochastic variables can be reduced. The socalled »rosette method» developed by the first author (P. Thoft-Christensen) is effective in this respect, because it handles the influence from position and direction relative to the pier independently of the other stochastic variables [10]. The applicability of the »rosette method» is demonstrated by a numerical example assuming that the fatal event originates from locking of the rudder.

2. EXTREME PEAK COLLISION LOADS

It is assumed that the relevant ships can be grouped into M classes of equal properties according to the parameters of importance to the peak impact collision (dead weight, impact velocity, bow construction, etc.). Further, the number of ship collisions against a specific pier from ships of class $i \in \{1, \dots, M\}$ during the time interval $]0, t[$ is specified by the counting process $\{N_i(\tau), \tau \in\,]0, t]\}$ (see [11]). Let $P_{i,j}, j \in \{0, \dots, N_i(t)\}$, $P_{i,0} = 0$, signify the j^th^ load from ships in class i. All $P_{i,j}$ are assumed to be identically distributed as P_i with the distribution function F_{P_i}.

The distribution function $F_{P_{max}}(\cdot, t)$ of the extreme impact force P_{max} in $]0, t]$ among impact forces from all considered M classes can then be derived under the following assumptions:

- The collision loads are mutually independent stochastic variables.
- The counting processes are Poisson processes with the intensities $\nu_i :]0, t] \curvearrowright R_0$ and are mutually independent.

One gets

$$F_{P_{max}}(p, t) = P(P_{max} \leqslant p) = \sum_{n_1=0}^{\infty} \dots \sum_{n_M=0}^{\infty} P(P_{1,0} \leqslant p \wedge P_{1,1} \leqslant p \wedge \dots \wedge P_{1,n_1} \leqslant p$$

$$\wedge \dots \wedge P_{M,0} \leqslant p \wedge P_{M,1} \leqslant p \wedge \dots \wedge P_{M,n_M} \leqslant p \mid N_1(t) = n_1 \wedge \dots \wedge N_M(t) = n_M) \times$$

$$P(N_1(t)=n_1 \wedge \ldots \wedge N_M(t)=n_M) = \sum_{n_1=0}^{\infty} F_{P_1}^{n_1}(p)P(N_1(t)=n_1)\times \ldots \times \sum_{n_M=0}^{\infty} F_{P_M}^{n_M}(p)P(N_M(t)=n_M)$$

$$= \prod_{i=1}^{M} \Big(\sum_{n_i=0}^{\infty} F_{P_i}^{n_i}(p)\frac{1}{n_i!}\Big[\int_0^t \nu_i(\tau)d\tau\Big]^{n_i} \exp\Big(-\int_0^t \nu_i(\tau)\,d\tau\Big)\Big)$$

$$= \exp\Big(-\sum_{i=1}^{M} (1-F_{P_i}(p))\int_0^t \nu_i(\tau)d\tau\Big) \tag{1}$$

3. FIRST PASSAGE TIME OF COLLISION LOADS

Let L signify the first passage time, i.e. the elapsed time until a collision load of magnitude p is exceeded for the first time. The distribution function F_L of L can then easily be determined because the event $\{L \leq t\}$ occurs if and only if the event $\{P_{max} > p\}$ occurs in the interval $]0, t]$.

$$F_L(t) = P(L \leq t) = P(P_{max} > p) = 1 - \exp\Big(-\sum_{i=1}^{M} (1-F_{P_i}(p))\int_0^t \nu_i(\tau)d\tau\Big) \tag{2}$$

If the Poisson processes are assumed to be homogeneous (ν_i independent of τ) then (2) reduces to

$$F_L(t) = 1 - \exp\Big(-\frac{t}{t_R}\Big) \tag{3}$$

where

$$t_R = \Big(\sum_{i=1}^{M} (1-F_{P_i}(p))\nu_i\Big)^{-1} \tag{4}$$

is the return period (expected first passage time) of peak impact forces exceeding the level p.

4. COLLISION RISK ASSESSMENT

The risk assessment can now be made either by specifying a specific fractile in the distribution function $F_{P_{max}}$ or alternatively by specifying a sufficiently large return period t_R. Note that $V[L] = 1$ so that e.g. the design level p will be exceeded at least once during the period $0.1\ t_R$ with a probability as high as $1 - e^{-0.1} = 9.5\%$.

The peak impact load depends primarily on the ship magnitude measured by the dead weight D, [3, 8, 9]. When the sample space $\Omega_D =]0, \infty[$ of D is divided into M disjoint intervals and $M \to \infty$ as the length of the subdivision passes to zero the Riemann sums in (1) and (4) converge. In the limit

$$F_{P_{max}}(p, t) = \exp\Big(-\int_{\Omega_D} (1 - F_P(p|x))\int_0^t d\nu(\tau, x)d\tau\Big) \tag{5}$$

$$t_R = \Big(\int_{\Omega_D} (1 - F_P(p|x))d\nu(x)\Big)^{-1} \tag{6}$$

where $F_P(\cdot|x)$ is the distribution function of impact loads on condition of $D = x$ and $d\nu(\tau, x)$ is the rate of ship collisions at time τ for ships with dead weight in the interval $]x, x + dx]$.

The last-mentioned quantity can be written

$$d\nu(\tau, x) = \nu(\tau|x)f_D(x)dx \tag{7}$$

where $\nu(\tau|x)$ is the collision rate on condition of $D = x$, and f_D the frequency function of D. If it is assumed that $\nu(\tau|x)$ can be written

$$\nu(\tau|x) = g(x)\nu_0(\tau) \qquad (8)$$

where

$$g(d_0) = 1 \qquad (9)$$

then ν_0 is the collision rate on condition of the scaling deadweight $D = d_0$ and $g(\cdot)$ weights the collision risks of ships different from d_0. (8) is valid, if the relative probability of collisions from ships of different magnitudes remain unchanged at all times. (5) and (6) can then be written

$$F_{P_{max}}(p, t) = \exp(-E[g(D)(1 - F_P(p|D))] \int_0^t \nu_0(\tau)d\tau) \qquad (10)$$

$$t_R = (\nu_0 E[g(D)(1 - F_P(p|D))])^{-1} \qquad (11)$$

The functions g, F_P and ν_0 are investigated further in the succeeding sections.

In more advanced models the peak impact load may depend on impact velocity, mass, bow construction etc. If these parameters are assembled in the vector valued quantity $\underset{\sim}{R}$ then the condition analogous to (8) is

$$\nu(\tau|\underset{\sim}{r}) = g(\underset{\sim}{r})\nu_0(\tau) \qquad (12)$$

The equations (10) and (11) are unaltered if the combined stochastic variables g(D) and $F_P(p|D)$ are replaced by $g(\underset{\sim}{R})$ and $F_P(p|\underset{\sim}{R})$.

5. RELATIVE RISK OF SHIP COLLISION

The function g weights the collision risk of ships different from the scaling deadweight $D = d_0$. Due to the fact that the beam of a ship is increasing with the deadweight d the probability of collision will increase with d. On the other hand it can be argued that larger ships will have relatively smaller probability of collision than smaller ships, because in greater ships the steering and safety systems are doubled, the crew is better trained, there will probably be a pilot on board, etc.

In lack of relevant data it is difficult to estimate the relative strength of these mutual reversed tendencies. Therefore, the best choice in this case is probably to select $g(d) \equiv 1$, and apply a scaling value d_0 in the vicinity of the final design load at the calculation of ν_0.

6. CONDITIONAL DISTRIBUTION OF IMPACT FORCES

As mentioned earlier to a first approximation the peak impact load P depends only on the magnitude of the ship d. Woisin has indicated a triangular distribution of P with the following conditional expected value [3, 8, 9] (see figure 1)

$$E[P|d] \sim 0.88\sqrt{d} \qquad (13)$$

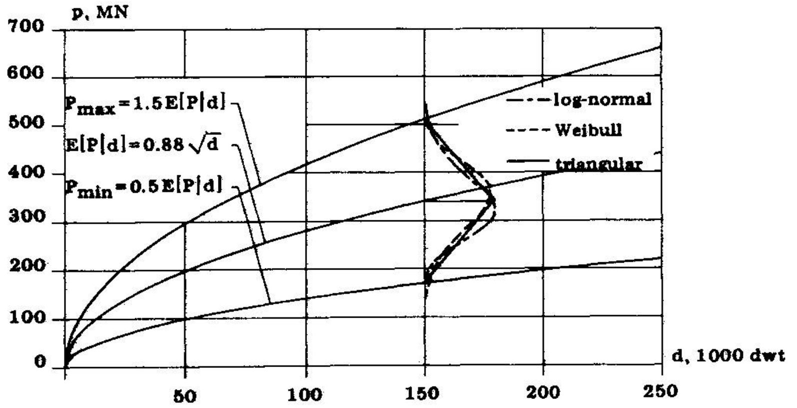

Figure 1. Conditional frequency functions of peak impact forces.

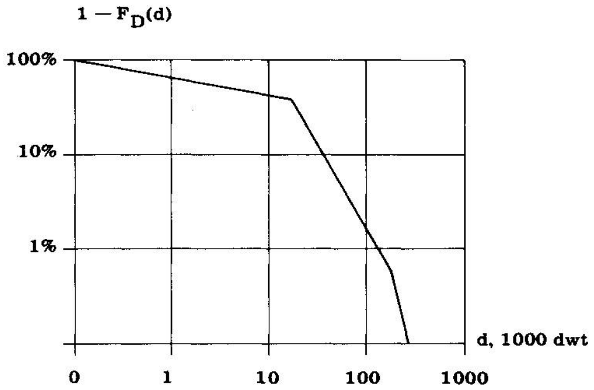

Figure 2. Complementary distribution function of magnitude of ships passing the Great Belt, Denmark, [2, 3].

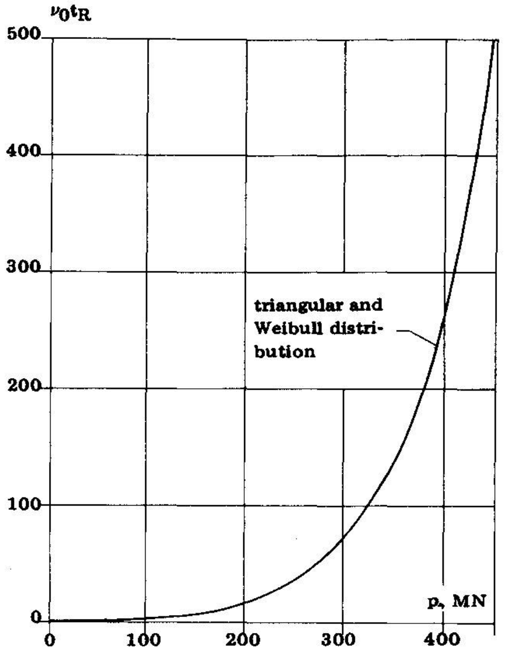

Figure 3. Non-dimensional return period as a function of design impact load.

Figure 1 also shows the density functions for the corresponding log-normal and Weibull distributions both with the same conditional expectation E[P|d] and the same conditional coefficient of variation $V[P|d] = 1/\sqrt{24}$ as the triangular distribution.

The non-dimensional return period $\nu_0 t_R$ (see (11)) can then be calculated as a function of the design impact load p if a distribution of deadweights D is chosen and by assuming $g(D) \equiv 1$. Let the distribution of deadweight D be as shown in figure 2 [2, 3], then the results corresponding to each of the three conditional distributions above are as shown in figure 3. The results are so close that only one curve is shown. The difference between the results is everywhere below 0.5%. As a consequence it can be stated that the non-dimensional return period $\nu_0 t_R$ is highly insensitive to moments in the conditional

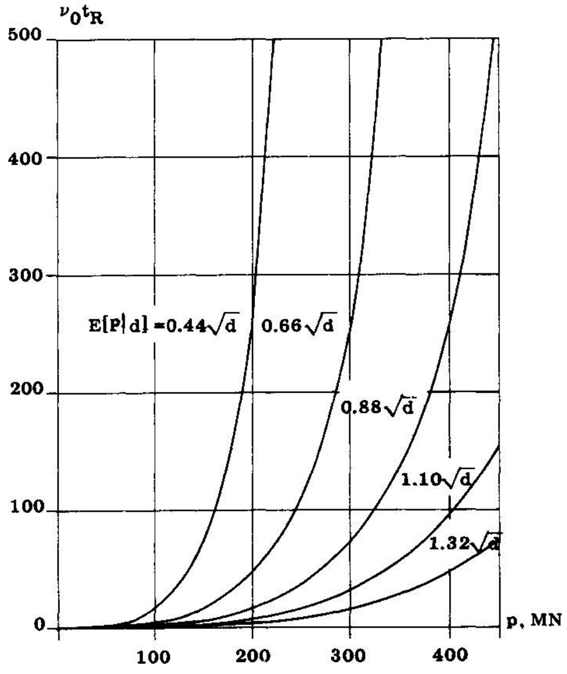

Figure 4. Non-dimensional return period. Dependence on conditional expectation of impact loads. Weibull distribution, $V[P|d] = 1/\sqrt{24}$.

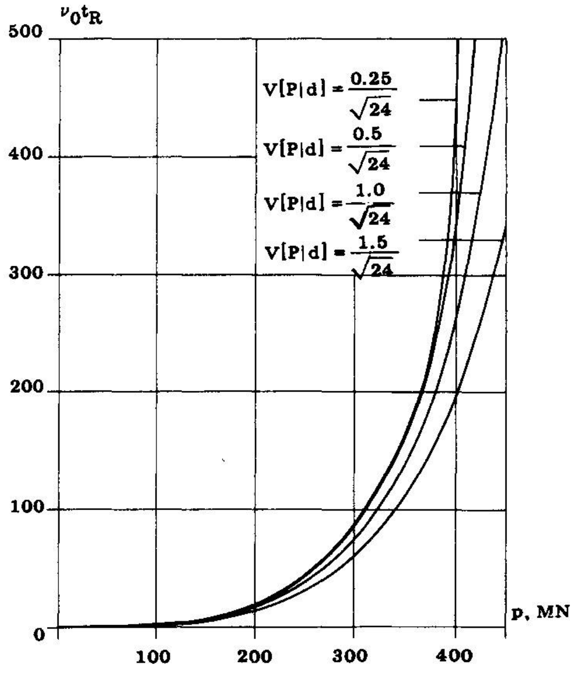

Figure 5. Non-dimensional return period. Dependence on conditional coefficient of variation. Weibull distribution, $E[P|d] = 0.88\sqrt{d}$.

distribution of P beyond the second moment properties. The dependence of $\nu_0 t_R$ on the second order moments is shown in figures 4 and 5. As expected the return period diminishes as the conditional expectation and coefficient of variation are increased. The dependence on the conditional expectation $E[P|d]$ is considerable. Therefore, the statistical errors inherent in the estimate (13) should be recognized, when the present method is applied.

7. ESTIMATION OF COLLISION RATE

Let a ship be characterized by the parameter set $\underset{\sim}{R} = \underset{\sim}{r}$ and consider the set of events E_i which renders the ship out of control and makes a collision to the pier possible. Let the probability rate of the event E_i be $\nu_{0,i}$ and let the event that ships with $\underset{\sim}{R} = \underset{\sim}{r}$ encounter the pier be denoted C. Then the collision rate $\nu_0(t)$ is

$$\nu_0(t) = \sum_i P(C|E_i)\nu_{0,i}(t) \tag{14}$$

where the conditional probabilities $P(C|E_i)$ are assumed to be independent of time. The failure rates $\nu_{0,i}$ must be estimated at best from available data.

On condition of the event E_i, the event C, i.e. collision with the pier takes place, is determined by a finite set of stochastic variables $\underset{\sim}{X}$, such as position of the ship, its speed and heading angle, speed and direction of wind and current, direction and height of waves, etc. at the instant of failure. The collision probabilities $P(C|E_i)$ can hardly be determined analytically. It is therefore necessary to estimate them by numerical simulation. Here a simulation method developed by Thoft-Christensen [10] will be demonstrated, when E_i signifies locking of the rudder at a random angle δ. Such a locking may occur during the continuous rudder manoeuvre due to the fact that unstable and neutrally stable ships cannot maintain a straight course without continuous rudder control.

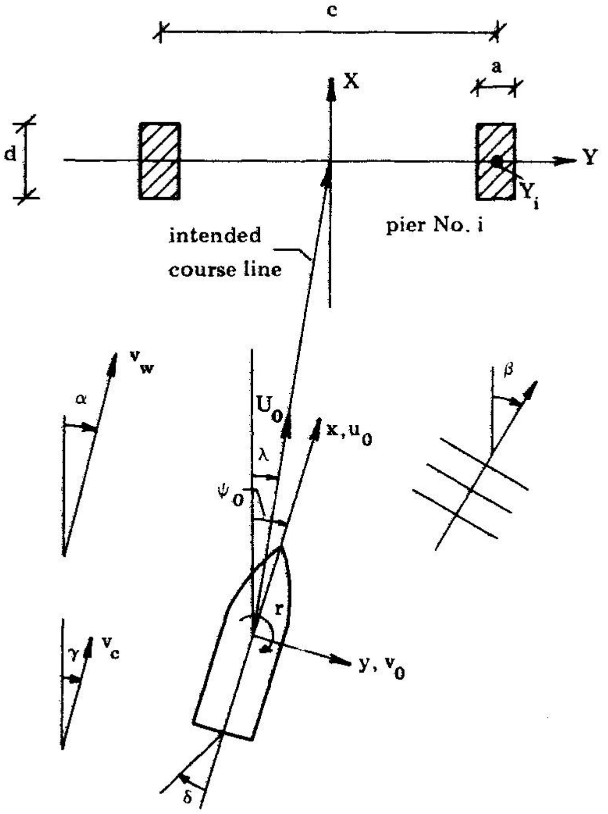

Figure 6. Decisive parameters of ship collision problem.

Ship positions are specified in relation to an inertial XYZ-coordinate system with origo at the centre of the free bridge span (see figure 6). In the same figure a body-fixed xyz-coordinate system is defined with origo somewhere in the symmetry plane and axes parallel to the principal axes of the ship.

The above-mentioned parameter set $\underset{\sim}{X}$ at the instant of failure contains at least the following stochastic variables:

X_0, Y_0, ψ_0: ship position and heading angle at failure
u_0, v_0, r_0: horizontal ship velocity components and yaw rate
δ: locked rudder angle at failure
v_w, α: wind speed and direction
h_s, β: significant wave height and direction
v_c, γ: current speed and direction

For the sake of simplicity it is assumed that all ships intend to approach the bridge in a straight course line towards the centre of the free span with speed U_0. Then

$$\left.\begin{aligned} X_0 &= -s\cos\lambda \\ Y_0 &= -s\sin\lambda \\ \dot{X}_0 &= U_0\cos\lambda \\ \dot{Y}_0 &= U_0\sin\lambda \\ r_0 &= 0 \end{aligned}\right\} \qquad (15)$$

where s is the distance to the centre of the free span and λ specifies the intended course line.

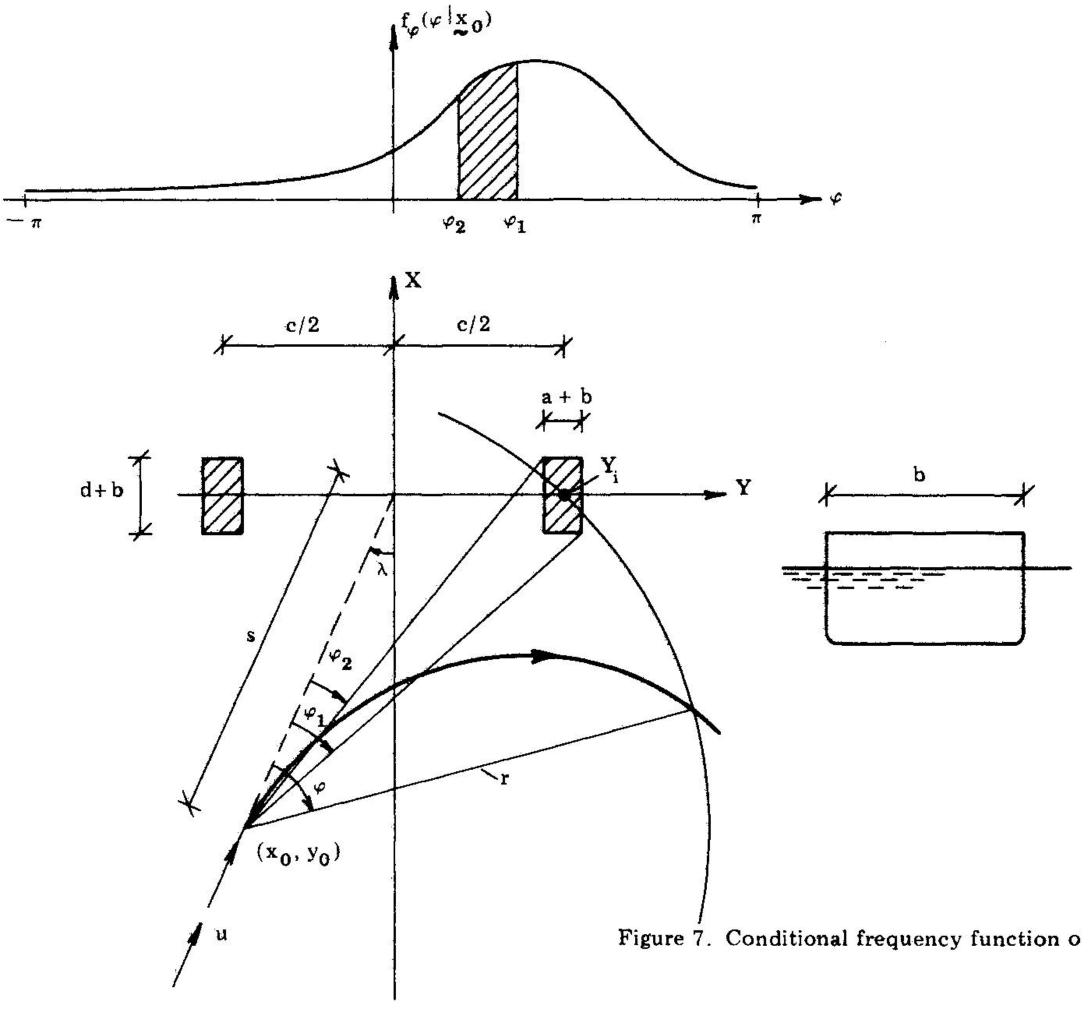

Figure 7. Conditional frequency function of collision angles.

Let the independent variables be grouped into the following two subsets $\underset{\sim}{X}_0 = (s, U_0, \lambda)$ and $\underset{\sim}{X}_1 = (\delta, v_w, \alpha, h_s, \beta, v_c, \gamma)$. The horizontal ship velocity components u_0, v_0 and the equilibrium rudder deflection depend on the parameters $\underset{\sim}{X}_0$ and $\underset{\sim}{X}_1$, and can be calculated from equilibrium conditions of the loads on the ship at straight course line.

The distance r to the considered pier at the instant of failure (locking of the rudder) depends only on the distance s and the angle λ (see figure 7). The trajectory of the ship will cross the circle with radius r at a certain angle φ, defined as shown in figure 7. This angle φ depends (on condition of the sample $\underset{\sim}{X}_0 = \underset{\sim}{x}_0$) merely on the stochastic vector $\underset{\sim}{X}_1$, i.e.

$$\varphi = f(\underset{\sim}{X}_1, \underset{\sim}{x}_0) \tag{16}$$

The ship will collide with the pier for $\varphi \in \,]\, \varphi_1, \varphi_2 [$ (see figure 7). Therefore, the conditional probability of collision $P(C|E_i)$, is given by

$$P(C|E_i) = \int_{\Omega_{\underset{\sim}{X}_0}} (F_\varphi(\varphi_1|\underset{\sim}{x}_0) - F_\varphi(\varphi_2|\underset{\sim}{x}_0))\, f_{\underset{\sim}{X}_0}(\underset{\sim}{x}_0)\, d\underset{\sim}{x}_0 \tag{17}$$

where $F_\varphi(\cdot|\underset{\sim}{x}_0)$ is the distribution function of φ on condition of $\underset{\sim}{X}_0 = \underset{\sim}{x}_0$ and where $f_{\underset{\sim}{X}_0}$ and $\Omega_{\underset{\sim}{X}_0}$ indicate the joint frequency function and sample space of $\underset{\sim}{X}_0$.

Clearly φ_1 and φ_2 depend on $\underset{\sim}{x}_0$ as well as the beam b of the ship and the dimensions of the pier. This fact can be taken into consideration by assigning equivalent dimensions a + b and b + d to the pier (see figure 7). Then the ship can be considered as a particle.

For sample values of the ship velocity U_0 and the angle λ a number of samples of $\underset{\sim}{X}_1$ are generated numerically. For each of these samples a ship trajectory is obtained from the manoeuvring equations governing the ship motion, and the crossing angles $\varphi_1, \varphi_2, \ldots$ at a number of concentric circles with preselected radii $r_1, r_2, \ldots$, are registered (see figure 8). From these sample values the conditional distribution functions $F_\varphi(\cdot|r_i, u, \lambda)$, $i = 1, 2, \ldots$, can be estimated. Actually the power of this so-called rosette method [10] originates from the fact that information is obtained for a great number of conditional distribution functions for each ship path realization.

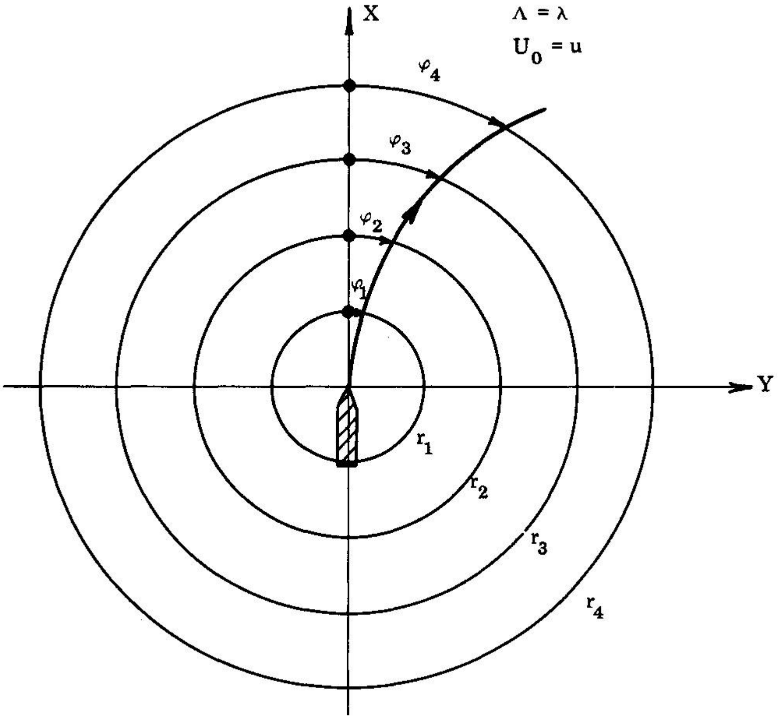

Figure 8. Collection of sampling values.

8. NUMERICAL EXAMPLE

In this section the method outlined above will be demonstrated with the following assumptions:

- $\lambda \equiv 0$
- Wave loads are ignored
- Wind direction is parallel to the Y-axis
- Current direction is parallel to the X-axis

Further it is assumed that the speed of wind and current are distributed according to the following Weibull distributions (v in m/s):

$$F_{v_w}(v) = 1 - \exp(-(\frac{v}{5.84})^{2.817}) \tag{18}$$

$$F_{v_c}(v) = 1 - \exp(-(\frac{v}{2.19})^{4.542}) \tag{19}$$

For a period of 75% of the time the wind direction is assumed to be in the positive Y-direction, whereas the current is directed in the positive and negative X-direction with equal probability. In both cases the directions are assumed to be independent of the corresponding speeds.

The density function f_Δ of the rudder angle δ is shown in figure 9. In the interval $[\delta_1 - 10°, \delta_1 + 10°]$, where δ_1 is the equilibrium value to maintain a straight course line, the density function follows a normal distribution with standard deviation $\sigma = 5°$. In some failure situations the rudder locks in the maximum rudder angle $\pm\delta_2$ with a probability of $\frac{1}{2}(1-p)$, where p is the probability of the distributed part of the sample space. In this example $p = 0.75$ and $\delta_2 = 35°$.

The distance s at failure between the ship and the bridge is assumed to be uniformly distributed in the interval [0, 4000 m]. Failures outside this interval are not considered to imply any risk of collision either because the ship can be stopped or collision can be prevented in other ways.

The ship velocity at failure U_0 is assumed to be Weibull distributed with expectation $E[U_0] = 8$ kn and standard deviation $\sigma_{U_0} = 2$ kn.

The hydrodynamic forces in the manoeuvring equations can be modelled either by the linear model of Abkowitz [12] or the non-linear model suggested by Norrbin [13]. In the present study the latter method has been applied with hydrodynamic coefficients taken from [14]. The wind coefficients of the ship are specified according to [15] and the manoeuvring equations are solved numerically by means of a 4th order Runge-Kutta integration scheme.

The conditional probability of collision is then calculated as a function of the width of the free span c and the result is shown in figure 10.

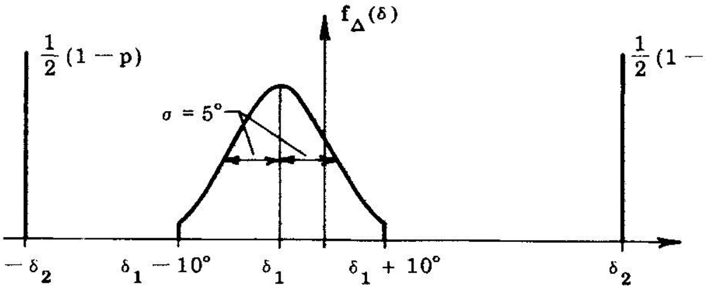

Figure 9. Density function of rudder angle at failure [10].

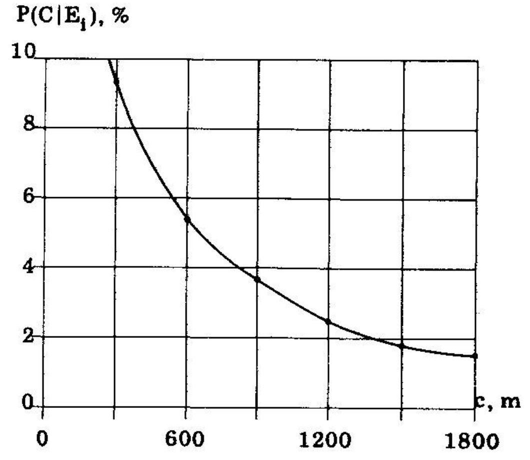

Figure 10. Probability of collision as a function of the free span c.

9. CONCLUDING REMARKS

A general method has been developed from which the distribution of extreme impact forces can be calculated. It is demonstrated how the reliability problem can be decoupled into two minor problems concerning the distribution of impact loads on condition that collision does take place and calculation of the probability rate at which larger ships will encounter the pier. A computer program has been developed from which the latter quantity can be calculated when rudder locking is the main cause of ship collision. Extension of the method to other failure sources is straightforward.

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Bridge Ship Collision Electronic Detection and Early Warning

Détection électronique et pré-alarme de collisions de ponts et de navires

Elektronisches Ortungs- und Frühwarnsystem für Schiffsbrückenkollisionen

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SUMMARY
This paper discusses the ship bridge collision problem and the use of early warning detection devices. The authors feel that the use of such devices may be of benefit and may possibly prevent bridge ship collisions.

RÉSUMÉ
Cet article traite du problème des collisions de bateaux et de ponts et l'utilisation d'appareils de détection avancée. Les auteurs sont d'avis que l'utilisation de tels appareils présente des avantages et pourrait prévenir les collisions entre ponts et bateaux.

ZUSAMMENFASSUNG
Dieser Aufsatz bespricht das Problem von Schiffsbrückenzusammenstößen und den Einsatz von Frühwarnungssystemen. Die Autoren behaupten, daß der Gebrauch solcher Geräte vorteilhaft sei, und Zusammenstöße zwischen Brücken und Schiffen verhindern könnte.

1. EFFECTS OF SHIP/BRIDGE COLLISIONS

Ships colliding with bridges often affect property, income, and human lives. Many of these lives might have been saved by effective collision warning systems. The Georgia Institute of Technology Engineering Experiment Station (GIT/EES) began formulating concepts for ship/bridge collision warning systems in 1972, shortly after a major accident near Brunswick, Georgia.

The Sidney Lanier Bridge near Brunswick, Georgia, was rammed by the freighter African Neptune on 7 November 1972. Ten people were killed. This was not an isolated incident.

A similar accident occurred during January 1975 when the Tasman Bridge spanning the Derwent River at Hobart on the Australian island of Tasmania was struck by the freighter Illawarra. Six persons died.

The Lake Pontchartrain Causeway in Louisiana has been damaged by waterway traffic 13 times since 1955. Nine persons were killed in these accidents.

On 24 February 1977, the sulphur carrier Marine Floridian smashed into the Benjamin Harrison lift bridge, dumping vehicles into the James River near Hopewell, Virginia.

On 9 May 1980, the Liberian bulk carrier M/V Summit Venture rammed a support pier of the western span of the Sunshine Skyway Bridge in Tampa Bay, Florida. Thirty-five people were killed.

2. CAUSE OF SHIP/BRIDGE COLLISIONS

Equipment failure, acts of nature, and human negligence are the primary causes of ship/bridge collisions. Human error caused the collision of the African Neptune with the Sidney Lanier Bridge.

Eight of the accidents involving the Lake Pontchartrain Causeway Bridge were caused by human negligence; five were caused by equipment failure. All but one of the accidents caused by negligence occurred at night or under twilight conditions.

The collision of the Summit Venture with the Sunshine Skyway Bridge can be attributed to the weather - the collision occurred as a storm suddenly blew across the bay area, cutting visibility and blanking the ship's radar. The time available after the collision, however, was more than sufficient to allow drivers approaching the broken span to stop safely, but they were not aware of the bridge condition ahead.

This fact is brought home in the National Transportation Safety Board's marine accident report[1] on the Sunshine Parkway Bridge Accident near Tampa, Florida. A motorist who was able to stop before driving through the hole left by the missing span recalled, "After I stopped, I remember that three cars and then a bus passed traveling southbound." The bus continued with no warning, carrying 26 people to their deaths.

The authors first suggested a solution to the problem of motorists driving off of a bridge with a severed span in a report prepared for the State of Georgia in 1973[2] on the subject of bridge hazards and their solutions. The authors recommended to the Georgia Department of Transportation that gates should be installed on the state's lift/draw bridges to stop vehicular traffic should bridge span over the shipping channel be severed.

One of the National Transportation Safety Board's recommendations is that the Federal Highway Administration develop standards for the design, performance, and installation of bridge span failure detection and warning systems.

There is a second system that could be developed to lower the probability of collision occurring in situations where human error is to blame for the vessel's collision with the bridge. The automatic collision early warning system was first proposed by Georgia Tech in 1973.[2] This system concept would be a cost effective alternative to consider where fendering systems to protect the bridge supports are impractical or not cost effective. The system would provide the pilot with precision data concerning vessel location and ground speed. This information would alert the pilot to mistakes made by the helmsman in the interpretation of rudder commands. The system could also protect motorists on the bridge by supplying an advanced warning of an impending collision, thus allowing motorists to clear the affected span(s). It could also actuate a gating system to ensure motorists who are not on the affected span do not enter the impact area of the bridge.

3. THE ELEMENTS OF AN EARLY WARNING SYSTEM

There must be seven basic elements included in the early warning system as defined by the Georgia Institute of Technology concept. These elements are:

1. The Vessel Tracking Sensor System must be capable of determining the location of the vessel of interest in relation to the waterway and the bridge to be protected. The sensor system must be able to provide not only real time vessel location, but also amplify data that will provide a prediction of future vessel position as a function of time.
2. The Environmental Sensor System provides data on the variables such as tide and wind. This data is required to improve the accuracy of vessel "future position" estimates.
3. The Sensor/Computer Interface converts the analog signals from the vessel tracking and environmental sensor systems to a digital format that can be treated as input data by a mini-computer.
4. The Radar Signal and Sensor System Processing Software Package is a computer resident program that processes the raw radar data, performs detection enhancement algorithms, performs target coordinate conversion routines, stores the processed radar data in temporary holding buffers, and processes and stores temporarily the wind and current sensor data for use by the assessment and warning algorithm.
5. The Pilot's Display System is a software driven communications link to the pilot. The purpose of this link is to give the pilot the vessel's ground speed and its location in relation to channel centerline. This data is transmitted to the pilot's hand-held display unit. The pilot's display shows the vessel's speed and location as referenced to the channel centerline. If a collision situation is predicted, the pilot would be warned by a visual "Collision Alert" annunciator, and a pulsed aural alert annunciator included on the pilot's hand-held display.
6. The Assessment and Warning Software is a computer program that models vessel handling characteristics based on vessel location, length, heading, past track history, and the effects of wind and tide.

   The vessel's computed future position is evaluated by the warning algorithm, on the basis of the data supplied by the assessment software. If the probability of collision is high, the warning algorithm computes the time to impact with the bridge and the probable point of impact. When ship handling characteristics are known, even the effects on position of last minute emergency maneuvers can be assessed with a high level of confidence.

7. The Warning Dissemination System is adaptive in nature and resides in both software and hardware. The software part of the system selects the appropriate motorist warning mode or modes in response to the threat. The warning function may include the selection of one of several voice warning messages for broadcast or an action message for display on the billboard. The system would also handle the closure of gates at specific locations on the bridge to stop traffic well behind the point of predicted impact.

4. THE ILLUSTRATED GEORGIA TECH CONCEPT

While elements of a collision warning system have been defined in a conceptual design, no fully automated system has been built around the Georgia Tech concept first proposed in 1973 in a Georgia Department of Transportation report[2] and again in 1978 in a paper[3] presented at The Bridge Engineering Conference, held in St. Louis, Missouri, and sponsored by the Transportation Research Board and again at the Conference on Bridge and Pier Protective Systems in 1981.[4]

Figures 1 through 4 illustrate the principles of the Georgia Tech concept. Referring to Figure 1, a high resolution shore based radar scans the waterway and detects the approaching vessel. A current and wind monitoring system is located in the vicinity of where the vessel begins lining up on an approach to the bridge. The high resolution radar provides the range and azimuth to the target. The resolution of the radar is high enough to allow the bow and stern to be resolved as individual radar cells. The high resolution range and azimuth profile of the vessel is processed by the tracking computer's radar signal and sensor system processing algorithm. As a track history is established, vessel speed, "gross" heading, and vessel distance from channel centerline become available data.

Figure 2 shows the display used by the pilot on the vessel to monitor the vessel's distance from channel centerline and "ground" speed. The computer supplies this data via a shore based radio transmitter link. The data is received by the pilot's hand-held display unit, and the speed and channel centerline information is displayed to the pilot. A row of eleven light emitting diodes display channel centerline distance on the hand-held unit. The different colored center diode would represent the channel center marker. Each of the five light emitting diodes located on either side of the center channel marker represents a discrete distance from the channel centerline. If the vessel is three increments (increment distance is chosen on the basis of radar resolution and channel width) to the left of channel centerline, the third light emitting diode left of the center channel marker would flash. This same information could also be displayed in digital read-out format where distance and drift rates could be shown as numeric values. Vessel speed would be displayed as a numeric value in units of knots. Other display formats are possible.

The importance of this data being provided to the pilot cannot be underestimated. Many of the ship/bridge collision reports studied by the authors show that during the critical time preceding the collision, the pilot either was unaware of his position on the waterway, did not detect an incorrectly interpreted rudder command, or lost his shore-based visual reference for an extended period of time.

Figure 3 shows one of several systems that could be used to provide motorists with one of several possible safety messages in the event of an impending collision. The system would broadcast a message via short range AM or FM carrier. In times of an emergency, the broadcast message would be selected by computer on the basis of the time until collision and predicted point of impact.

Figure 4 shows the back-up approach of a "billboard" used as a general warning system. The sign displaying the message "SHIP IN TROUBLE" or a similar warning would be used as a first warning to motorists without a radio or those who do not monitor the warning channel.

5. THE GEORGIA TECH DESIGN CRITERIA

The first goal of the Georgia Tech design criteria was to eliminate the need for any location system that would require the navigation equipment normally found on board the veseel to be used as part of the vessel location scheme. Use of the vessel's own systems was avoided due to the fact that there is no way to certify calibration of the shipboard systems, and in some cases, the basic operability of the equipment.

A second criteria was that any system to be carried on board the vessel by the pilot would not be larger than a "handi-talkie." Rigging of special transmitters or receivers on the vessel on a temporary basis was rejected outright. This rejection is due to the unorthodox methods used to transfer pilots between the pilot vessel and the "host" vessel, and the general reluctance of some pilots to "fool with newfangled equipment."

A third criteria was that the location system should be primarily a shore based system with built-in calibration test.

A fourth and most important criteria is that the system can not require all vessels to maintain the same "ground track" regardless of their size or short term wind, tide and harbor river traffic conditions. There are many harbors where the "ground track" of a vessel will never be the same for any point in time during the vessel's approach to the bridge, due to the effects of the aforementioned variables. In fact, the "track lines" will change from hour to hour and vessel to vessel if any maneuvering is required.

A fifth criteria was that no system would be developed that takes any responsibility away from the pilot.

The sixth and last criteria was that the system would not require the vessel to be extremely "off track" before issuing a collision alarm. However, it was realized that the system false alarm rate must be extremely low if the system is to maintain credibility with the public.

6. THE WARNING SYSTEM SENSOR

Radar is attractive for application to the detection of ship navigation problems because range and angular resolutions can distinguish the bow, stern, and heading of even small vessels. Furthermore, moderate amounts of signal processing can provide real-time information on the vessel's present location, heading, and velocity along with predicted future positions. Thus, the radar can derive a precise vector that fully describes the dynamic situation (position, direction, and magnitude) of a vessel under track. The radar and signal processor can simultaneously accommodate as many targets (ships) as desired. The coverage area along with any fixed objects of significance can be stored in the signal processor such that a vessel's position and future position relative to those fixed objects and other vessels in the coverage area is readily available.

The radar and signal processor data can be recorded easily on magnetic tape; thus, a permanent record of all activities in the coverage area is available.

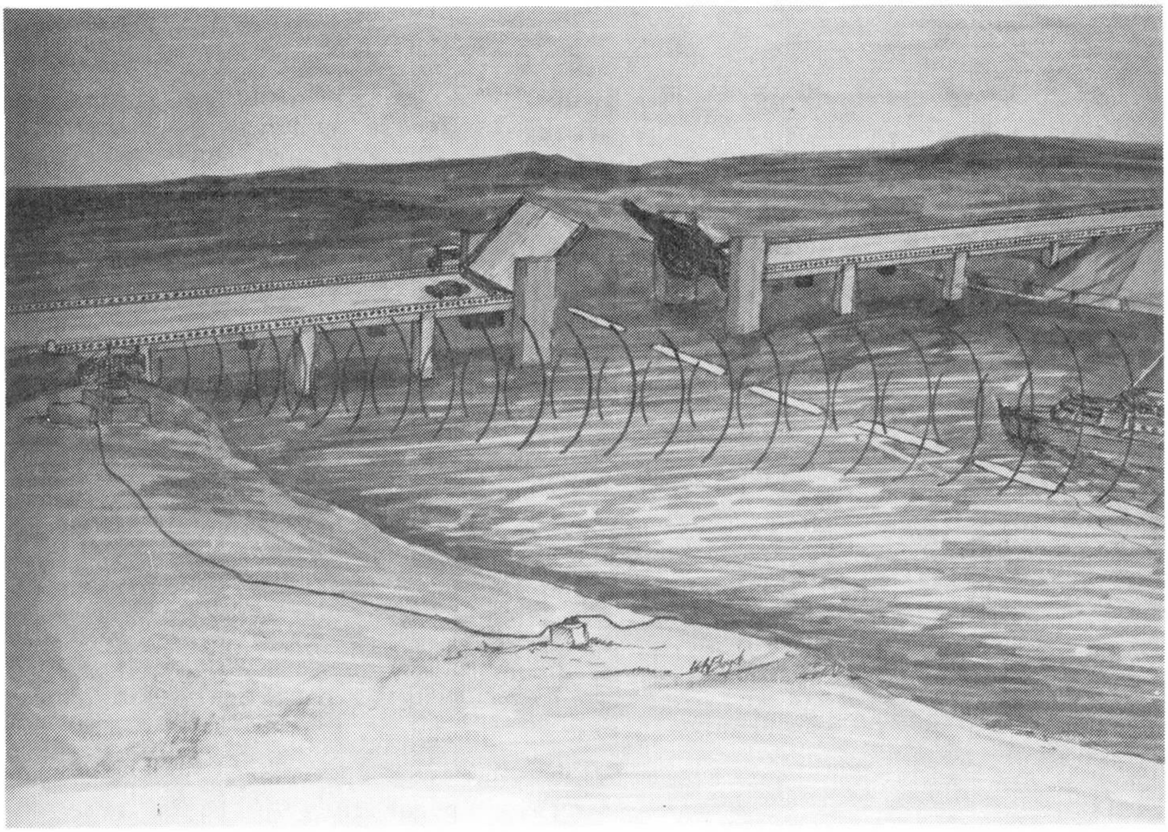

Fig. 1. Shore based radar monitors approach of vessels while wind/current sensors monitor environmental factors.

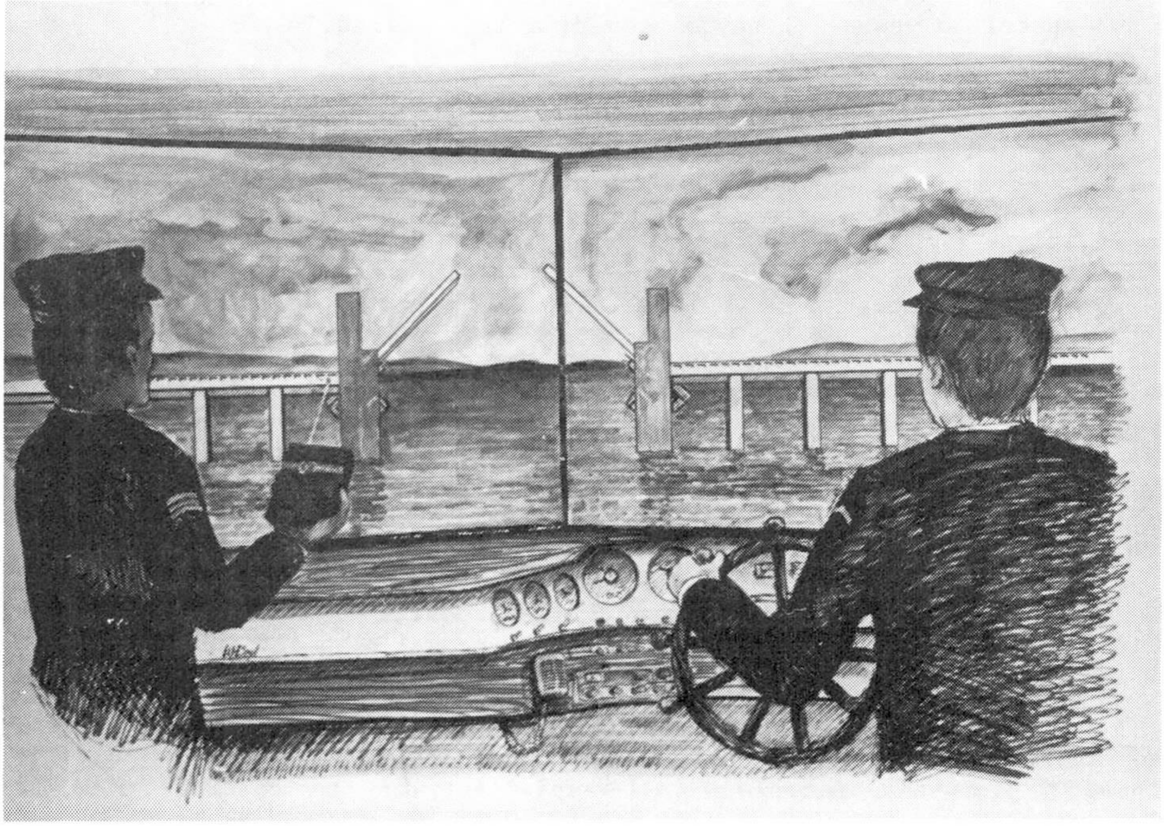

Fig. 2. The pilot using a hand-held telemetry data link showing vessel location in relation to the center channel line and vessel speed.

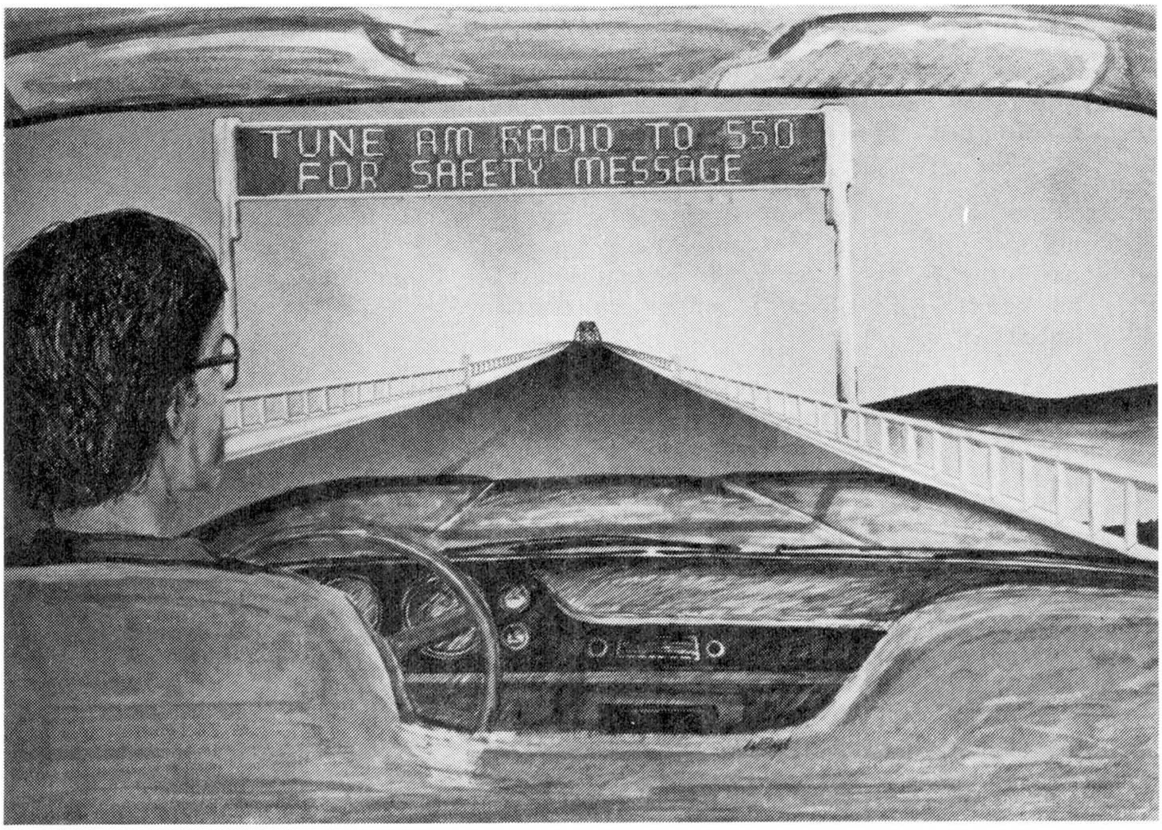

Fig. 3. Sign showing motorists the instructions on how to use the safety information radio system.

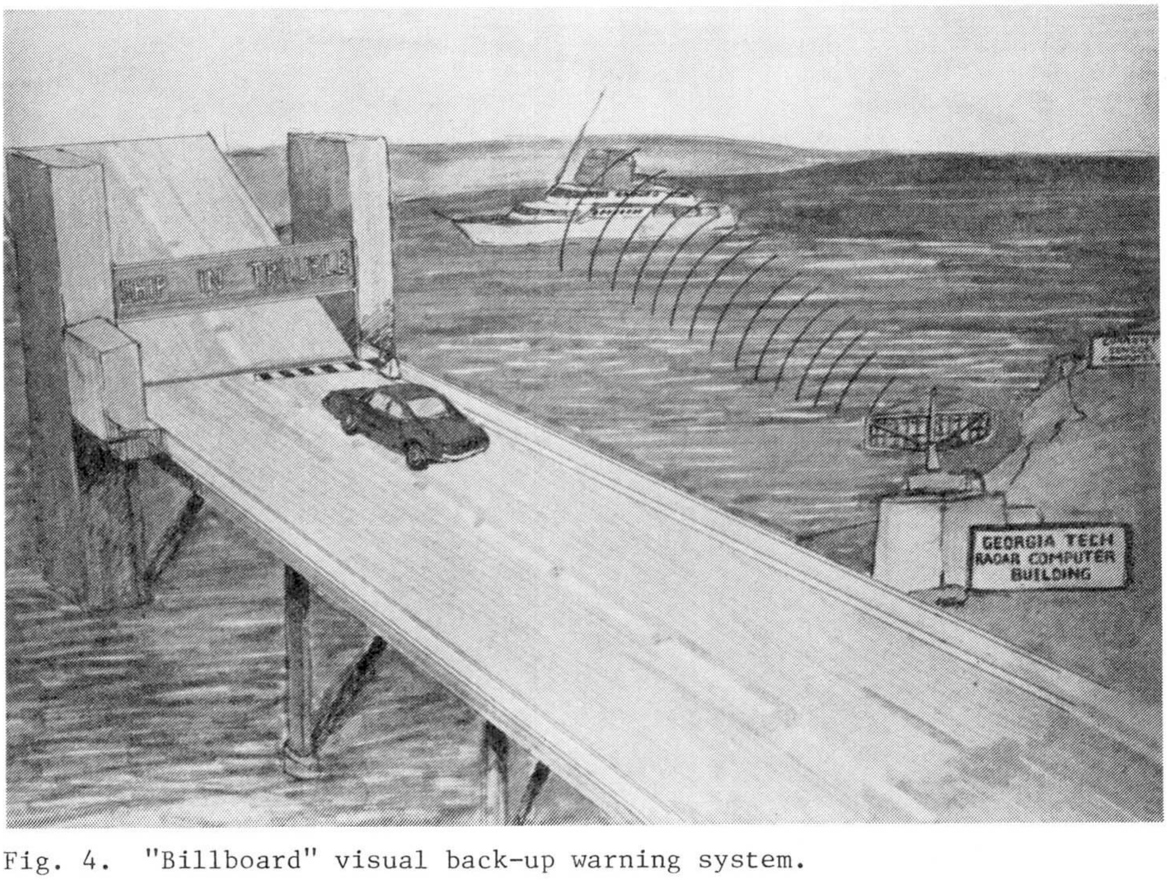

Fig. 4. "Billboard" visual back-up warning system.

6.1 Radar System Analysis

The optimum radar configuration for a given collision avoidance application must be derived from a system and trade analysis of various parameters associated with the geometry of the desired coverage area, the meteorological/hydrographical environments, and the radar itself.

The geometry of the area to be covered will dictate where the radar must be located and how high the antenna must be elevated above surrounding area. Once the geometry of the coverage area and the location of the radar are specified, the ranges (distances) to the perimeter of the desired coverage area are readily obtainable.

If the collision avoidance system must operate under severe meteorological and/or hydrographical conditions, the radar must be designed with the worst case effects of those adverse environments factored into the system performance requirements.

7. SUMMARY

The collision warning system outlined appears feasible. A first system must be funded, built and tested to generate the "numbers" to prove feasibility, acceptability, and cost benefit.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. W. H. Boyd for the illustration of the Georgia Tech concepts. We would also like to thank the Georgia Department of Transportation for funding the first Georgia Tech study that led to the development of the concepts outlined in this paper.

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Probabilistic Modeling of Ship Collision with Bridge Piers

Modèle de la collision d'un navire contre les piles d'un pont

Wahrscheinlichkeitsmodell der Schiffskollision mit Brückenpfeilern

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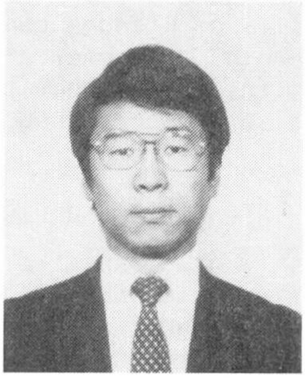

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SUMMARY
This paper presents a model to estimate the probability of ship collision with bridge piers constructed over a strait or bay. The model includes, at the operational variables, the design variables such as the span length and the pier diameter, the traffic volume and the fairway width. Some numerical examples of the collision probability for these variables are also presented. In computation, statistical data collected in Japan are used.

RÉSUMÉ
L'article présente un modèle pour estimer la probabilité de collision d'un navire contre les piles d'un pont construit au-dessus d'un détroit ou d'une baie. Les variables de conception telles que la portée du pont, le diamètre des piles, le volume du trafic et la largeur de la voie maritime sont pris en considération. Quelques résultats numériques de la probabilité de collision sont calculés, sur la base de données statistiques au Japon.

ZUSAMMENFASSUNG
Ein Modell wird vorgeschlagen, um die Wahrscheinlichkeit einer Schiffskollision mit Brückenpfeilen in einer Meerenge oder Bucht abzuschätzen. Die Bauparameter einer Brücke, wie zum Beispiel die Spannweite und der Pfeilerdurchmesser, und der Verkehrsumfang von Schiffen werden hier als die operativen Variablen behandelt. Ferner werden einige numerische Ergebnisse der Kollisionswahrscheinlichkeit für diese Variablen anhand der statistischen Daten in Japan gezeigt.

1. INTRODUCTION

Ships carrying hazardous material such as oil and LNG tend to increase in number and size. On the other hand, a number of maritime structures such as oil-platforms and bridges over a bay or strait recently become to be constructed. Therefore, once a ship happens to collide with those structures, there will be tremendous losses and damages.

Taking these situations into account, not only the structural safety but also the ships' navigational safety should be considered in planning and design of those structures.

This paper discusses a model to estimate the collision probability of ships with a bridge pier. The model has been developed based on the model proposed previously by the authors ([1], [2]). In order to give useful information for planning and design of bridges constructed over a bay or strait, this model includes the span length, the pier diameter, the fairway width and the marine traffic characteristics as the operational variables. Numerical examples by the proposed model are also presented and discussed.

2. FACTORS INFLUENCING SHIP COLLISIONS

The authors ([1]) classified the factors which influence the collision of ships with obstacles in or near the fairway such as the bridge piers and other offshore structures as shown in Table 1. These factors can be devided into two groups : operational factors and non-operational ones.

In the operational factors, fairway width, curvature and obstacles are related to location and design of the structure. In case of bridges, the fairway width and obstacles are represented by the span length and the pier cross-sectional diameter, respectively, and the curvature partly depends on the location of the bridge. Since this paper aims to obtain the probability of ship collision with a bridge pier, the factors of fairway length, fairway crossing and fairway side shape are not considered explicitly. Curvature of the fairway is assumed to be infinite. That is, the fairway is assumed to be straight under given bridge location. However, it should be notified that these fairway characteristics can not be omitted in case of the probability of collisions between ships.

In the non-operational factors, navigator's and natural conditions are implicitly taken into consideration as the random variation of the distance where the ships start their give-way motions to avoid the collision with the bridge pier.

Table 1 Factors Influencing Collisions

Operational		Non-Operational		
Channel Characteristics	Traffic characterstics	Navigators Characteristics	Ship Characteristics	Natural Conditions
1. Fairway Width	1. Ship Size Distribution	1. Quality	1. Ship Size	1. Tidal Stream
2. Fairway Length	2. Sailing Velocity Distribution	2. Illegal Sailing	2. Speed Performance	2. Wave
3. Depth	3. Total Traffic Volume	3. Bad Watching	3. Steering Performance	3. Sight Distance
4. Curvature	4. Traffic Volume Ratio in Different Directions	4. With or Without Pilot	4. Stopping Performance	4. Wind Direction
5. Fairway Crossing	5. Crossing Traffic Volume		5. Radar Equipment	5. Wind Force
6. Navigation Mark	6. Wake Position Distribution			6. Weather
7. Obstacles	7. Headway Distribution			7. Time
8. Channel Side Shape				

3. PROBABILITY MODEL OF SHIP COLLISION

3.1 Modeling Process

As shown in Fig. 1, the basic consideration starts with modeling the give-way motion of a ship of particular size, B_k, sailing at the position X_k.The collision of this ship with the bridge pier is defined as the event of failure of the give-way. This is given by the function of B_k, X_k, the pier diameter, D, fairway width,W, span length,L, and the distance l_k,between the ship and the center of the pier section when the ship starts give-way motion. Hereafter, the distance,l_k, is called as the give-way starting distance (GWS-distance). Since the GWS-distance can be regarded as a random variable, the event of failure of give-way becomes a random event. The probability of occurrence of this event is defined as the " failure probability of give-way", and denoted by P_f. On the other hand, the sailing position,X_k, can be considered as a random variable whose probability density function (p.d.f.), $\phi_X(X_k/W,Q)$, is specified by the fairway width and the traffic volume per hour, Q. Thus the expected failure probability of give-way, P_{ef}, is given as a function of B_k, D, W, and Q. Based on this probability, probability of ship collision, P_c, is obtained.

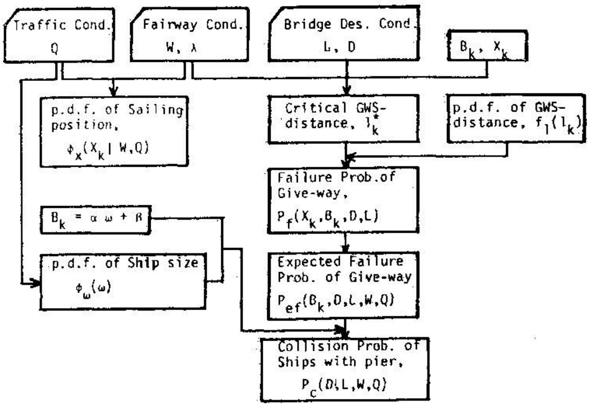


Fig. 1 Modeling Process of Collision Probability

3.2 Failure Probability of Give-way

As discussed in the previous section, modeling the give-way motion is the basis of a mathematical treatment of ship's collision with a bridge pier. Suppose a ship of particular size, B_k, sailing at the position, X_k, with the velocity,V_k, takes a give-way motion (Fig. 2a). In general the give-way motion includes altering course by steering, speed-down , anchoring, and so forth. However, the present model consideres only the steering motion because speed-down, anchoring and other motions are quite rare comparing with the steering motion. Let l_k be the distance between the ship and the pier in the y-coordinate when the ship starts the give-way by the angle , θ , of altering course (see Fig. 2b). The distance , d(t), between the center of the ship and the pier when time t is passed after starting the give-way motion is given by

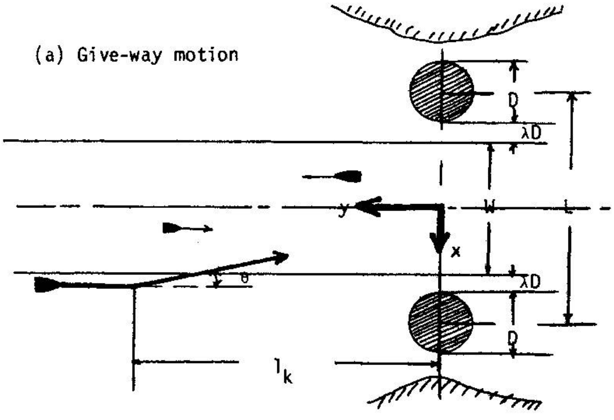
$$d(t) = [\{X_k - V_k t \sin\theta - \frac{L}{2}\}^2 + \{l_k - V_k t \cos\theta\}^2]^{1/2} \qquad (1)$$

in which

$$L = W + (2\lambda + 1)D \qquad (2)$$

This is reduced on the assumption that the ship can be approximated by the circle of diameter, B_k, which denotes the

(a) Give-way motion



(b) Critical GWS-distance

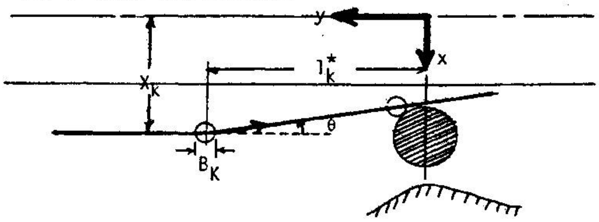


Fig. 2 Give-way Motion and Critical GWS-Distance

width of the ship. Eq.(1) gives the minimum distance, d^*, as

$$d^* = l_k \sin\theta + (X_k - \frac{L}{2})\cos\theta \tag{3}$$

Then the collision of the ship with the pier is defined as the event that the distance, d^*, is less than equal to the "collision diameter, D_{ck}", which is defined by

$$D_{ck} = (B_k + D)/2 \tag{4}$$

that is,

$$d^* \leqq D_{ck} \tag{5}$$

Applying Eqs.(3) and (4) to Eq.(5), the critical distance, l_k^*, is given by the following equation :

$$l_k^* = D_{ck}\operatorname{cosec}\theta + (X_k - \frac{L}{2})\cot\theta \tag{6}$$

The critical GWS-distance, l_k^*, means that the ship will collide with the pier if she starts the give-way motion at the distance to the pier less than l_k^*. In the practical situation, ships start the give-way motions at the various distance depending on the conditions of their own instruments and navigators and others. Based on the authors' observational data at Obatake in Japan, the GWS-distance, l_k, follows lognormal distribution as shown in Fig. 3. Thus the p.d.f. of l_k is approximated by

$$f_1(l_k) = \frac{1}{\sqrt{2\pi}\, l_k \sigma_1}\exp[-(\frac{\log l_k - \mu_1}{\sqrt{2}\,\sigma_1})^2] \tag{7}$$

In the above equation, the mean μ_1 and the standard deviation σ_1 could be a function of the conditions discussed previously. For instance, the observational data by the Ministry of Transpotation of Japan ([3]), the GWS-distance under head on situation between two ships is the function of their velocities and sizes. However, enough data of GWS-distances are not collected to identify the function statistically. Therefore, in this paper the GWS-distance l_k is assumed to follow a lognormal distribution with constant mean and standard deviation.

Taking into account that l_k follows the lognormal distribution, the failure probability of give-way, P_f, is calculated as follows :

$$P_f(X_k, B_k, D, L) = \text{Prob.}[\, l_k \leq l_k^* \,] = \begin{cases} \frac{1}{2}[1+\text{ERF}(\frac{I_{ck}}{\sqrt{2}})] & \text{for } X_k \leq X_k^* \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

wher ERF(·) is the error function, I_{ck} and X_k^* are given by

$$I_{ck} = \frac{\log l_k^* - \mu_1}{\sigma_1} \tag{9}$$

and

$$X_k^* = \frac{W + 2\lambda D - B_k}{2} \tag{10}$$

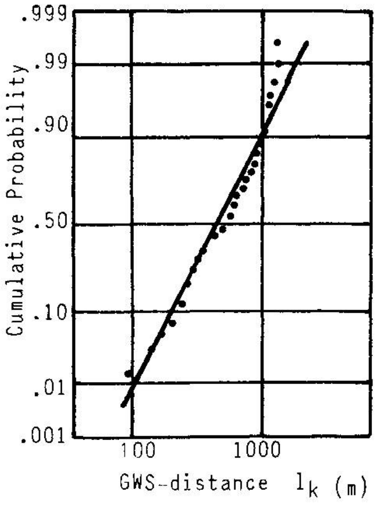


Fig. 3 Prob. Distribution of GWS-distance, l_k.

3.3 Collision Probability

Ships can be expected to take their sailing position on the fiarway at their will. However, their positioning could be affected by the fairway conditions and the traffic condition. Inoue ([4]) reported that the sailing position is affected by the fairway width and the traffic volume per hour modified by the ship length, and that the sailing position follows the normal distribution as shown in Fig. 4.

According to his conclusions, the mean sailing position , μ_x , in a two-way traffic fairway of width , W , can be approximated by

$$\mu_x = a\,W \tag{11}$$

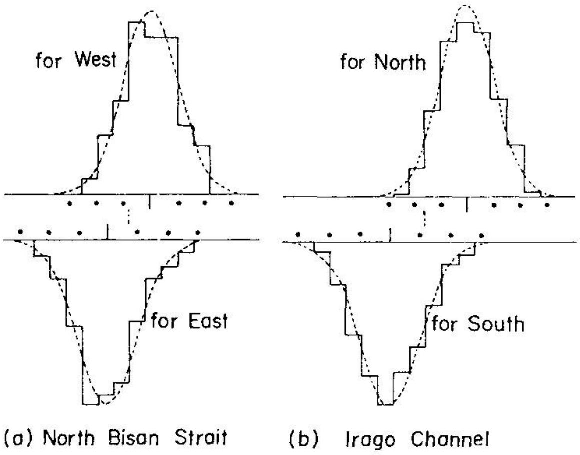
where a is a constant defined for the given fairway conditions, that is,

a = 0.2 with centerline mark

a = 0.1 without centerline mark

and the standard deviation of sailing position ,σ_x, in a certain direction on the two-way traffic fairway is

$$\sigma_x = -7.170+0.105W+2.168Q_L^* \tag{12}$$



(a) North Bisan Strait (b) Irago Channel

Fig. 4 Distribution of Sailing Position

in which W is measured in meter and Q_L^* is the traffic volume per hour modified by the ship length when the standard ship length , L_s^* , is employed as $L_s^* = 35$ m. Eq.(12) means that sailing position in x-direction (see Fig. 2b) tends to spread outer side of the fairway as the width and the traffic volume increase.

The modified traffic volume Q_L^* is calculated by the traffic volume , Q', per hour in a certain direction and its ship size distribution.Based on the data presented by Fujii ([5]), the ship length in the traffic volume Q' follows the lognormal distribution. Namely, denoting ω as the natural logarithm of ship length L_s,

$$\omega = \log_{10} L_s \tag{13}$$

the p.d.f. of ω is given by

$$\phi_\omega(\omega) = \exp[-\frac{1}{2}(\frac{\omega-\mu_\omega}{\sigma_\omega})^2]/\sqrt{2\pi}\,\sigma_\omega \tag{14}$$

Using Eq.(14), the modified traffic volume Q_L^* in Eq.(12) can be calculated by

$$Q_L^* = Q'\int_0^\infty 10^\omega\,\phi_\omega(\omega)d\omega \tag{15}$$

From Eqs.(11) and (12), the p.d.f. of X_k is given by

$$\phi_x(X_k \mid W,Q') = \exp[-(\frac{X_k-\mu_x}{\sqrt{2}\,\sigma_x})^2]/\sqrt{2\pi}\,\sigma_x \tag{16}$$

Applying Eq.(16) to Eq.(8), the expected failure probability of give-way, P_{ef}, is

$$P_{ef}(B_k,D,L,W,Q') = \int_{X_k^*}^{\infty} \frac{1}{2}[\,1+\mathrm{ERF}(\frac{I_{ck}}{2})]\,\phi_x(X_k \mid W,Q')dX_k \tag{17}$$

This probability is the elementary probability in the sense that any one ship of size B_k is expected to have the probability P_{ef} to collide with the pier under the hourly traffic volume ,Q'. Therefore, when 0 traffic volume per year is expected and Q_k ships of size B_k exist in Q, the Probability, P_{sk}, that any ship of Q_k does not collide with the pier is

$$P_{sk}(D,L,W,Q',Q) = (1-P_{ef})^{Q_k} \doteq 1-P_{ef}\,Q\,\phi_\omega(\omega_k)d\omega_k \tag{18}$$

Therefore, the probability that all of Q ships do not collide with the pier is

$$P_s(D,L,W,Q',Q) = 1-Q\int_0^\infty P_{ef}\,\phi_\omega(\omega_k)d\omega_k \tag{19}$$

In the above integration it should be noticed that P_{ef} is the function of ω_k, because B_k has a unique relationship with the ship length L_k. Fujii ([5]) gives the relation as follows

$$B_k = \alpha\, \omega_k + \beta \;, \qquad \alpha = 0.88, \qquad \beta = -\, 0.47 \tag{20}$$

Since P_S gives the probability that none of the ships of volume Q collide with the bridge pier, the probability that at least one ship collides with the pier is approximated by

$$P_c(D,L,W,Q',Q) = 1 - P_s = Q\int_0^{\infty} P_{ef}\, \phi_\omega(\omega_k)d\omega_k \tag{21}$$

where

$$Q' = Q \,/\, 8760$$

3.4 Average Number of Collision Ships

Since every ship of size B_k is expected to have the elementary probability of collision, the probability that N_k ships of Q_k will collide with the pier is given by the binomial distribution as

$$P_c(N_k) = \binom{Q_k}{N_k} (\, 1 - P_{ef})^{Q_k - N_K}\; P_{ef}^{\;N_k} \tag{22}$$

This gives the average number , $\bar{N}_k$, of collision ships of size B_k as

$$\bar{N}_k = P_{ef}\, Q_k \tag{23}$$

Therefore, the average number, $\bar{N}_c$, of collision ships when total traffic volume Q per year is expected is given by

$$\bar{N}_c = Q\int_0^{\infty} P_{ef}\, \phi_\omega(\omega_k)d\omega_k \qquad [\text{ships/year}] \tag{24}$$

This has the same form as Eq.(21). However, Eq.(21) is the approximate form of the probability. Therefore, it does not exceed unity even if Q becomes very large number, while Eq. (24) gives the average number of collision ships if it goes over unity.

4. NUMERICAL EXAMPLES AND DISCUSSION

In computation of numerical examples, the values of the parameters in the model are used as shown in Table 2. The angle of altering course , θ , is based on the fact that the steering angle used by most of the ships in altering their courses is about 15 degree. The mean, μ_1, and the standard deviation, σ_1, of GWS-distance are from the data observed at Obatake in Japan (see Fig. 3)

Table 2 Values of Parameters Used in Examples

$\theta = 30°$ $\quad$ $\mu_1 = 6.15$

$\alpha = 0.88$ $\quad$ $\sigma_1 = 0.59$

$\beta = -0.47$ $\quad$ $\mu_\omega = 1.40$

$a = 0.2$ $\quad$ $\sigma_\omega = 0.15$

The statistical parameters , μ_ω , and , σ_ω , of the ship size distribution are assumed from those of the traffic in some straits in Japan (Fujii[5]).

Fig. 5 gives the relation between average number $\bar{N}_c$ of collision ships per year and the span length under a given fairway width and the traffic volume. From this figure, it can be understood that the number of collision ships will decreases as L increases. This is resultant from that the marginal space between the fairway edge and the pier becomes large as the span length increases. However, according to the authors' previous study ([2]), the average number of collision between ships per year does no change so long as the fairway width is constant. This is shown by the dotted line in the figure. On the contrary, in Fig. 6 is shown the relation between N_c and the fairway width under constant span length. In this case, the number of collision ships increases as the width increases. This might be felt strange. However, it should be notified that when the fairway width increases the marginal sea space decreases and in addition, ships tend to sail widely out of the fairway as shown in Eq.(12). While the number of collision between ships is reduced when the fairway width increases. This is also shown by the dotted line in the figure. The trade-off between them should be considered in planning and design of bridges over a strait or bay.

Fig. 7 gives the relation between $\bar{N}_C$ and the traffic volume under a constant L and W. This can be intuitively understood.

5. CONCLUDING REMARKS

From these numerical results, it can be expected that under the traffic volume Q = 900 ships per day and the span length L = 1 km, and the fairway width W = 800m, ship collision with the pier is expected once in every two years.

The proposed model has many assumptions and simplifications. However, this model is expected to give useful information for planning and design of maritime structures such as bridges over sea, oil-platforms in the sea and so forth. Further developed model is under studied by the authors.

6. ACKNOWLEDGEMENT

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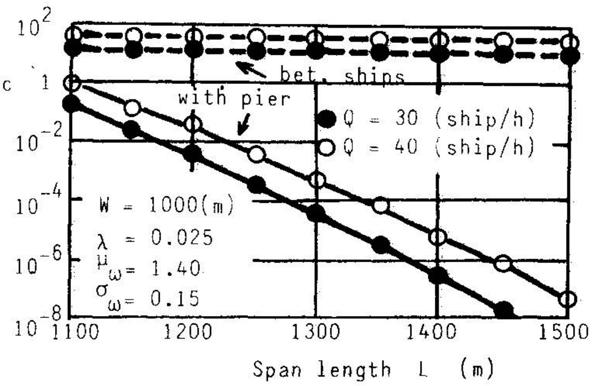

Fig.5 $\bar{N}_C$~L Relation

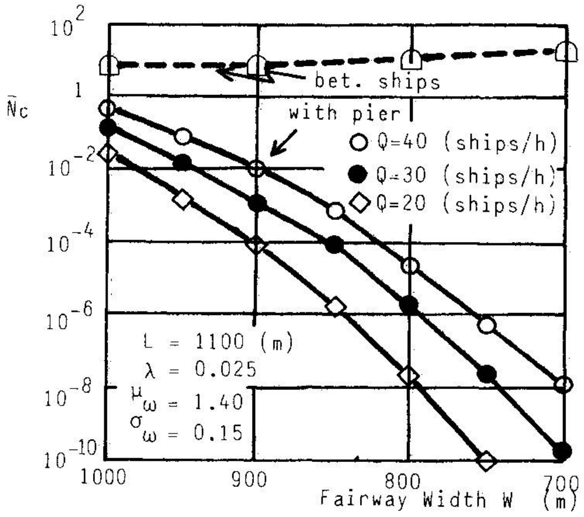

Fig.6 $\bar{N}_C$~W Relation

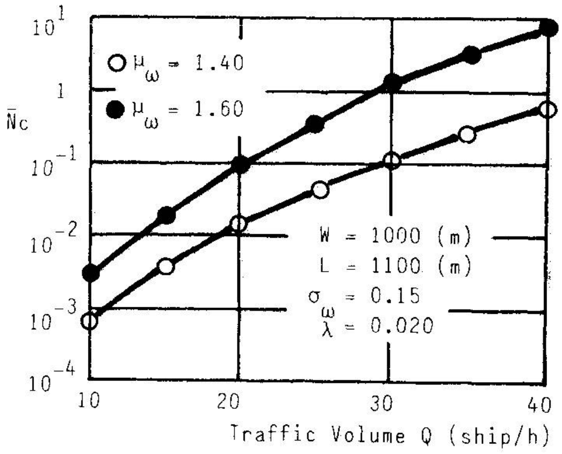

Fig.7 $\bar{N}_C$~Q Relation

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Transportation Risk Modeling of Tanker Ship Operation

Modèle d'analyse de risque pour la navigation des pétroliers

Modelle für die Risikoanalyse in der Tankerschiffahrt

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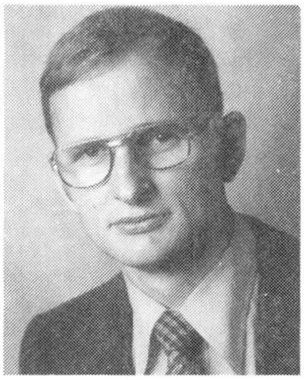

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SUMMARY

Fault tree methodology is applied to quantify transportation risk of marine traffic systems comprising potential catastrophic events. Operational conditions and risks as well as structural failures are modeled. Main concepts of modeling include local and temporal subdivision of the system.

RÉSUMÉ

L'analyse logique de la sécurité ou du risque des systèmes navals présentant une grande quantité de dangers et de facteurs opérationnels est réalisée à l'aide de la méthode d'arbre de défauts. Les méthodes de calcul sont expliquées avec l'exemple du trafic des pétroliers dont la structure est variable dans le temps et dans l'espace.

ZUSAMMENFASSUNG

Zur rationalen Erfassung von Zuverlässigheit oder Risiko bei Seeverkehrssystemen mit hohem Gefahrenpotential und überwiegend operativen Komponenten wird die Fehlerbaumtechnik eingesetzt. Die Methoden der Berechnung und der Modellierung werden am Beispiel des Tankerverkehrs erläutert, wobei die logische Struktur vor allem nach lokalen und zeitlichen Bereichen gegliedert wird.

1. INTRODUCTION

To calculate the reliability of a complex system rationally we need a method, which enables us to model the system's behaviour and to quantify its relevant characteristics. In this context, also for assessing alternatives under the economic aspect, it is important to incorporate into the model information on "mechanical" as well as on "operational" reliability. We define components or events related to technical hardware as "mechanical", and components or conditions resulting from operation and handling as "operational". In marine traffic operational system components are of major significance. To a high degree they depend on the traffic situation and in particular on human factors. A reduction of risk by increasing the reliability of mechanical components may be more costly or of less effect upon overall reliability. Of course, if marine traffic would become a highly automated system, the main emphasis would have to be placed on the hardware.

2. COMPUTATIONAL MODEL

Fault tree methodology is a suitable tool to analyse systems with high potential risks. A fault tree model is obtained by collecting all events of relevance for a current top event (e.g. collision) and linking them according to their causal relationships by logical operators (AND, OR). Given the probability of occurrence of basic events, i.e. of events not considered as being caused by other events, it is possible to compute the importance of individual components or sets of components quantitatively (e.g. as reliability importance).

Let y_i be the state indicators of the n components (basic events) of a system, with

$$y_i = \begin{cases} 1, & \text{in case of occurrence of the event} \\ 0, & \text{in case of non-occurrence of the event} \end{cases} \tag{1}$$

then the state of the system is characterized by the value of the structure function:

$$s_F = s_F\,(y_1, \ldots\ldots\ldots\ldots, y_n) = s_F\,(\underline{y}) \tag{2}$$

with

$$s_F = \begin{cases} 1, & \text{in case of occurrence of the top event} \\ & \text{(system failure)} \\ 0, & \text{in case of non-occurrence of the top event} \end{cases} \tag{3}$$

Index F indicates that the structure function models a failure; y_i are indicators for occurrence of failures or of conditions favouring the occurrence of failures. For the purposes of quantitative analysis the design function of large systems is usually represented with the aid of min cut sets M_j and min path sets W_j. If n_M is the number of min cut sets and n_W the number of minimum path sets, the structure function of the system can be expressed by

$$s_F(y) = \prod_{j=1}^{n_W}\Big(1 - \prod_{i\in W_j}(1-y_i)\Big) = 1 - \prod_{j=1}^{n_M}\Big(1 - \prod_{i\in M_j} y_i\Big) \tag{4}$$

If Y_i are the random quantitites of the basic event states, the following applies for the expected value of the structure function:

$$E\left[\prod_{j=1}^{n_W}\left(1-\prod_{i\in W_j}(1-Y_i)\right)\right] \le E\left[S_F(Y)\right] \le E\left[1-\prod_{j=1}^{n_M}\left(1-\prod_{i\in M_j}Y_i\right)\right] \tag{5}$$

With $q_i = P[Y_i = 1] = E[Y_i]$, and assuming statistically independent basic events, the following rough estimate holds [6]:

$$\prod_{j=1}^{n_W}\left(1-\prod_{i\in W_j}(1-q_i)\right) \le E\left[S_F(Y)\right] \le 1-\prod_{j=1}^{n_M}\left(1-\prod_{i\in M_j}q_i\right) \tag{6}$$

If Y_i equals 1 after occurrence of event i at time t (otherwise $Y_i = o$) and assuming constant failure rates λ_i the following applies

$$q_i(t) = E\left[Y_i(t)\right] = 1 - e^{-\lambda_i t} \tag{7}$$

Of course, the absolute value of a failure probability thus calculated is of minor significance, since bounds of acceptable risks are difficult to define. However, the effects of changes in the probability of occurrence of basic events or of changes in the tree structure allow practically relevant decisions with respect to system safety. A measure of importance, which takes into account structural importance and probability of occurrence of a component i, is the reliability importance, [6]:

$$I_i = \frac{\partial S_F^*(q_i)}{\partial q_i} = S_F^*(1_i, \underline{q}) - S_F^*(0_i, \underline{q}) \tag{8}$$

S_F^* is the random value of the structure function S_F reduced according to idempotency of Boolean variables ($y_i \cdot y_i = y_i$); $S_F(1_i, \underline{q}) = (S_F(\underline{q})$ with $q_i = 1)$ and $S_F(0_i, \underline{q}) = (S_F(\underline{q})$ with $q_i = 0)$; $\underline{q} = (q_1, q_2 \ldots q_n)$.

Narrower bounds than those given in (5), (6) are [7]:

$$E\left[S_F\right]\begin{cases} \le E\left[\prod\limits_{i\in M_1} Y_j\right] + \sum\limits_{j=2}^{n_M}\left(E\left[\prod\limits_{i\in M_j} Y_i\right] - \max\limits_{k=1}^{j-1}\left(E\left[\prod\limits_{i\in M_j} Y_i \prod\limits_{i\in M_k} Y_j\right]\right)\right) \\ \ge E\left[\prod\limits_{i\in S_1} Y_j\right] + \sum\limits_{j=2}^{n_M}\max\left(0,\ E\left[\prod\limits_{i\in M_j} Y_i\right] - \sum\limits_{k=1}^{j-1} E\left[\prod\limits_{i\in M_j} Y_i \prod\limits_{i\in M_k} Y_j\right]\right) \end{cases} \tag{9}$$

The preparation of this kind of risk model includes two major tasks: development of the logical tree structure and collection or theoretical acquisition of basic event data. Structural and quantitative analysis of the model is left to computer programs, [1,2,3,4,5].

3. DEVELOPMENT OF TREE STRUCTURES

Fault tree modeling for marine transportation requires a specific methodology. Automatical tree generation by computer is not possible due to the lack of a detailed definition of the system. One modeling method (type 1) is to derive subtree structures for local areas (e.g. harbour, traffic separation scheme) from relevant events occurring there. However, such a subtree is of little use when developing subtrees for other areas. Generalisation will hardly be possible. This may also lead to structural weaknesses of the overall model. Another approach (type 2) appears more appropriate. An overall tree structure is developed. Considering one essential element of the system, e.g. the tanker, some critical events are chosen (e.g. collision, grounding, ramming). All other events with relevance to the critical events are collected and linked in subtrees. The same procedure may be repeated within the subtrees down to the basic events, for which probability data have to be specified. Subsequently, such basic models are adapted to the conditions prevailing in the local area considered e.g. by omitting irrelevant substructures and adjusting probability data. Structural adaptations can be made by setting events TRUE or FALSE or by using an editing program [4]. Thus, when developing new trees, existing subtrees can be used. This procedure considers that a theoretical model is never perfect and therefore has to be supplemented by experience gained during its practical application.

Another essential factor is the degree of resolution of the model: It is, for instance, not possible to model human error only by one basic event. On the other hand, it is not practicable to model any conceivable detail of what may happen. Another important concept is the introduction of time frames (according to [8]), relating events to:

- the short-time frame, if events occur in critical situations, when the time remaining to take preventive measures is very short, so that system failure becomes highly likely;
- the intermediate-time frame, if events combine giving rise to a critical situation, unless successfully prevented;
- long-time frame, if events relate to general misjudgements, miscalculated risks, etc., which may contribute to an accident at a later stage.

If the behaviour of system components is not in compliance with binary logic, it can be modeled by comparison with threshold values. The fault tree structure should be preapred with regard to data availability. Finally, the model should be verified with the aid of case studies.

4. SAMPLE MODELS OF TANKER OPERATION

A type 1 model (according to [9]) developed from local areas is shown in Fig.1. This model structure was subdivided with respect to critical events (collision, grounding, ramming) and below this level with respect to local areas. Thus, ramming of a bridge in area 3 has been modeled in a separate subtree, while other events in area 3 can be found in the subtree "collision". A collision scenario was also developed in detail in [10] by means of directed graphs [11]. The concept of a safety zone moving with the critical object (tanker) is introduced, within which the object is surrounded by a smaller critical zone; Fig.2.

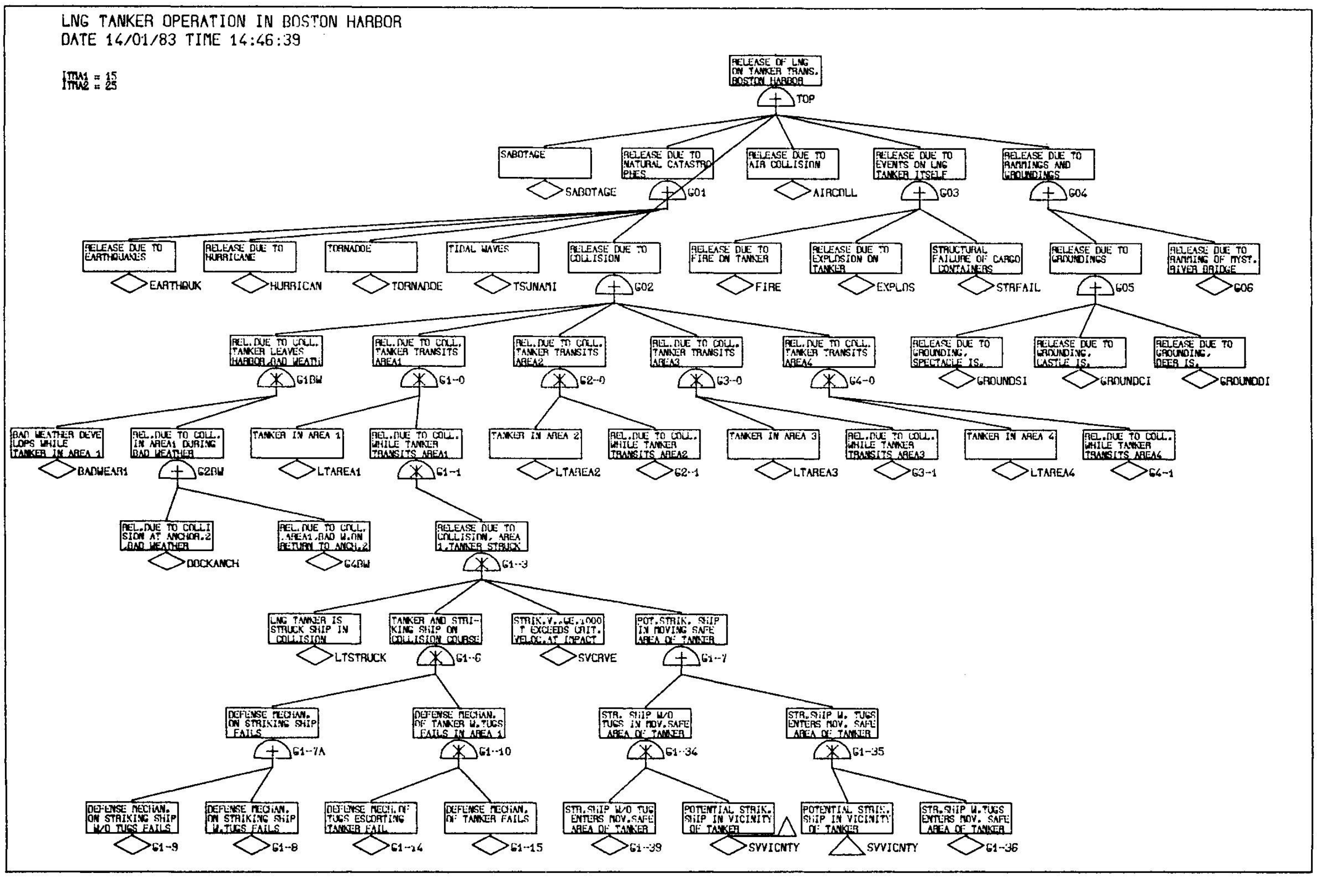

Fig.1: Portion of a type 1 model, LNG tanker operation in harbour, [9].

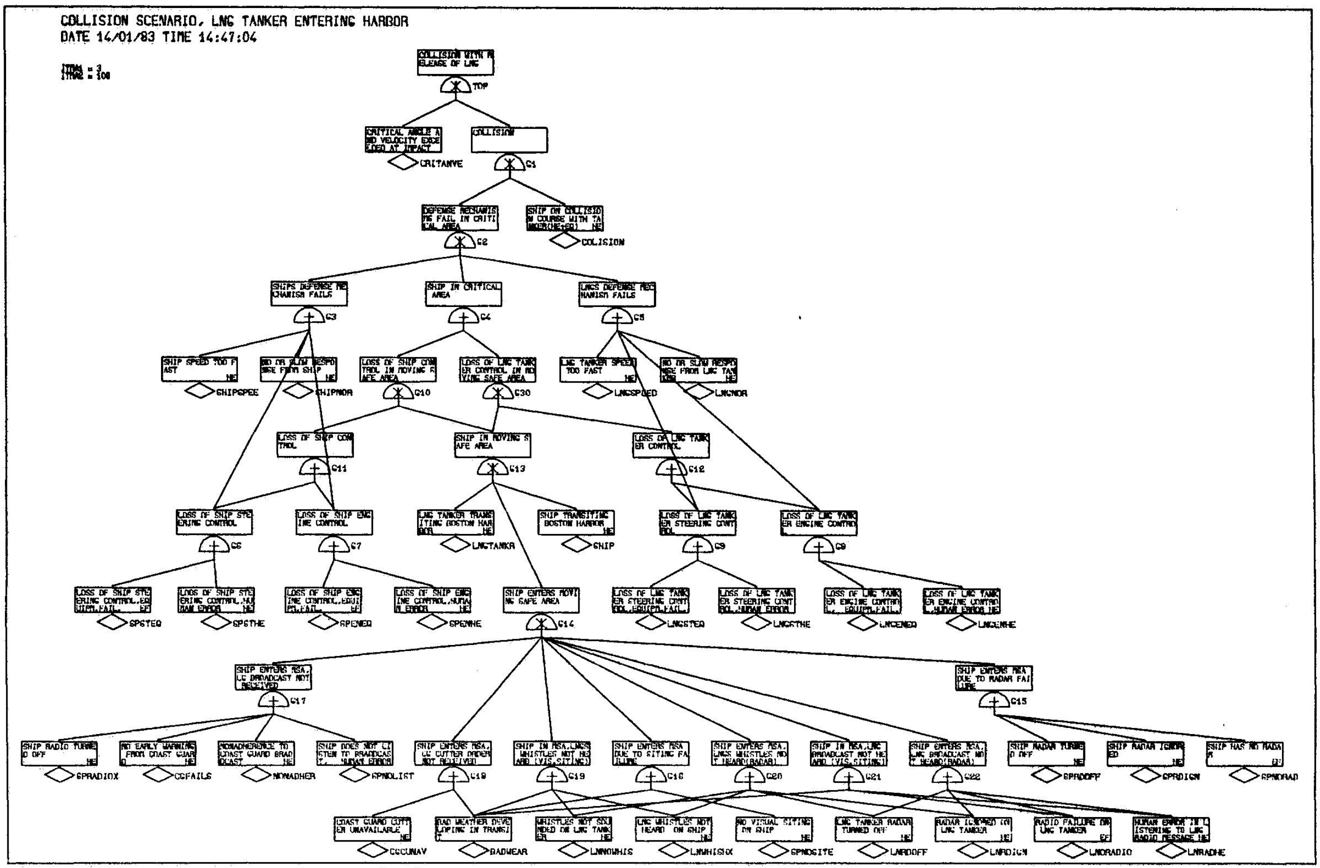

Fig.2: Collison scenario, [10].

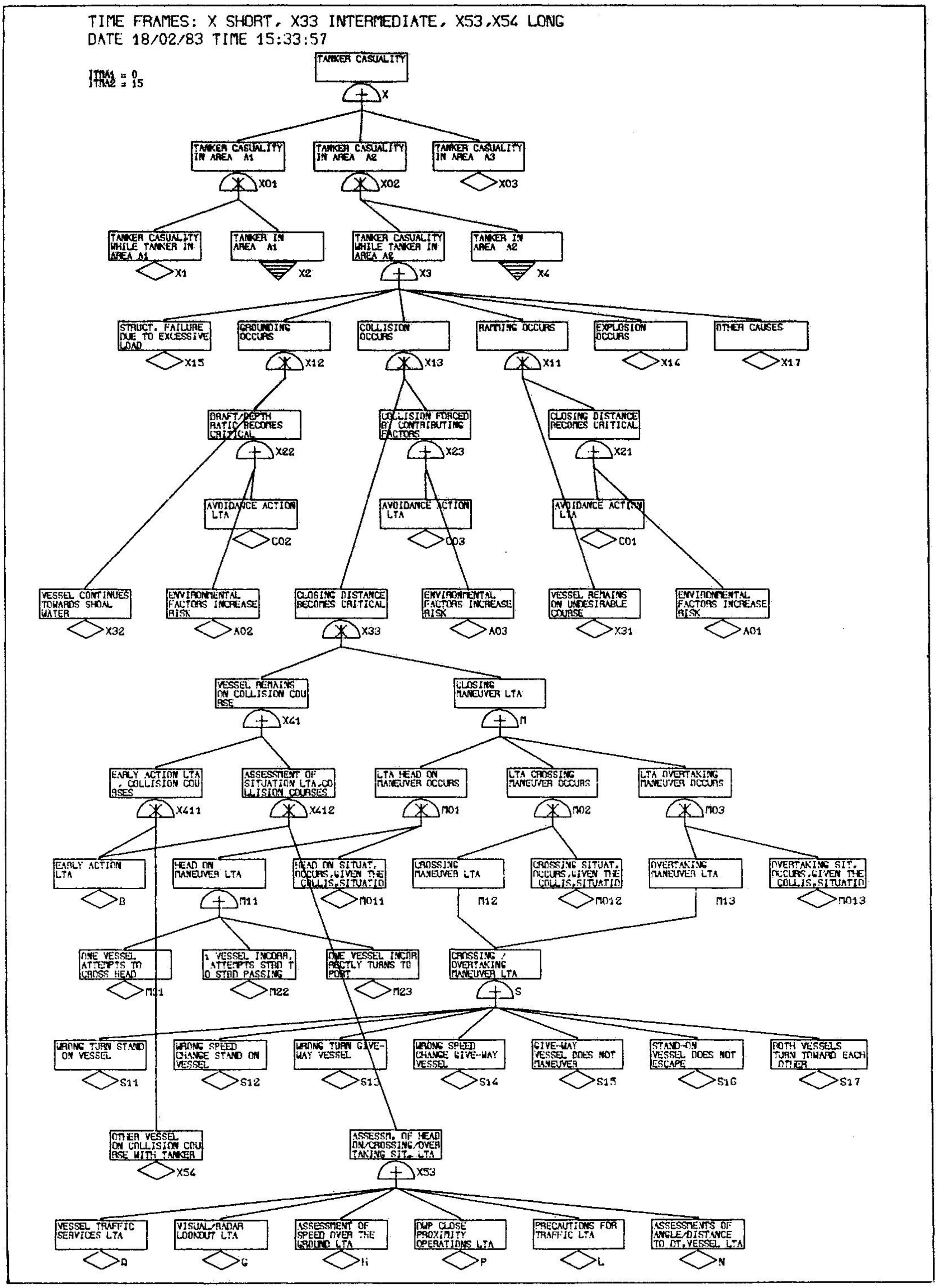

Fig.3: Portion of type 2 model, tanker operation

Starting from the approach made in [8] a type 2 model is developed to analyse tanker traffic in the Heligoland Bight. Operational components (e.g. due to navigation, environmental conditions, human factors) and mechanical components (such as structural failures, equipment failures) are included in the model. Local areas are chosen with respect to traffic flow characteristics, geographic restrictions of waterway, jurisdiction objective of the investigation, etc..

A subdivision of the fault tree structure corresponding to local areas can be seen in the upper part of Fig.3 (events X01, X02, X03 ...). Critical events X11, X12, ..., X17 are top events of separate subtrees. The short time frame is above X31. The long time frame ranges from the X31 level to the X53 level. The long time frame is below X 53. Nearly all events in Fig.3 are further analysed in detailed subtrees. Only X2 and X4 are basic events, the probabilities of which result from the mission profile of the tanker. Event X54 is estimated in relation to shipping density.

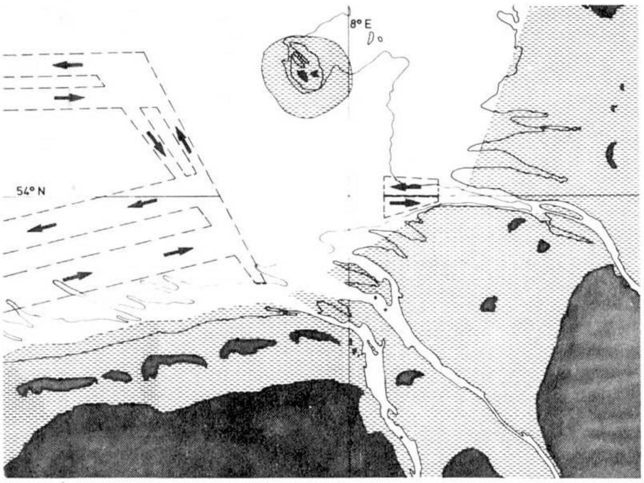

Fig.4 Heligoland Bight, general view

5. CONCLUSION

Some advantages of the fault tree approach are the more rational analysis of system behaviour, capability of sensitivity studies and of comparing alternate systems or subsystems. To make the results more informative, more reliable basic event data have to be collected. Particularly for operative components some uncertainty exists. Data may also be obtained from modern nautical simulators. Correlations of operative events might be introduced to quantitative analysis in the way it is done for mechanical components in [12], [13]. Possible safety measures could be optimized, if component cost functions can be established.

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Risk of Ship Interference with Submarine Pipelines

Risque d'interférence de navires avec des conduites sous-marines

Gefahr der Kollision von Schiffen und Rohrleitungen

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SUMMARY
Statistical data on ship accidents and ship course aberrations exist, but data on ship interference with pipelines are negligible. This paper describes the application of a deterministic approach to the evaluation of the risk of ship-pipeline interference on the basis of available ship failure event statistics. It also refers to the evaluation of the consequences of such events.

RÉSUMÉ
Des statistiques sur les accidents de navigation et les erreurs de navigation existent, mais des informations sur l'interférence de navires sont rares. Cet article décrit une méthode déterministe de l'évaluation du risque de l'interférence des navires avec des conduites sous-marines sur la base de statistiques d'accidents de navigation. L'évaluation des conséquences de ces événements est également mentionnée.

ZUSAMMENFASSUNG
Statistische Daten über Schiffahrtsunfälle und verirrte Schiffahrtskurse sind vorhanden, doch sind Daten über Schiffskollisionen mit Rohrleitungen unerheblich. Diese Abhandlung beschreibt die Anwendung eines deterministischen Verfahrens, um die Gefahr einer Schiff-Rohrleitungskollision auf Basis vorliegender Statistiken über Schiffahrtsunfälle zu beurteilen. Sie bezieht sich auf die Abschätzung der Folgen eines solchen Unfalles.

1. INTRODUCTION

Ship accident risks (anchoring and grounding) are a dominant factor in the overall risk picture of a marine pipeline crossing of a restricted navigational channel.

This is particularly the case in the Danish Great Belt, which accommodates Transit Route T, the main shipping route between the North Sea and the Baltic, and where the shipping risks have been a very important consideration for decisions on trenching depth, route location, and the number and spacing of pipes in the gas transmission system crossing.

There exists a reasonable amount of statistical data on ship accidents and ship course aberrations, but the statistical information on ship accidents involving pipelines is negligible and certainly insufficient to build any risk evaluation up on. Thus while a stochastic approach could be used to determine the probable incidence of ship aberration events, it was necessary to use deterministic methods to interpret these events in terms of the risk of pipeline damage for the Danish Great Belt Gas Transmission Crossing. No computational tools were ready to hand, and it was therefore necessary to develop new procedures taking as a starting point published work by Fujii and MacDuff.

These new deterministic procedures were based on geometrical and soil mechanics considerations.

It is important to emphasize that calculations of the type referred to here (examples of which are given in References A, B, and C) cannot be accurate and can do no more than indicate orders of magnitude. The results derived must be interpreted in this light.

It should be noted that the examples of design and safety data relating to the Danish gas transmission system marine pipelines are presented here merely to illustrate the methodology and should not be taken as representing the final design or safety levels of that system.

2. SHIP ANCHORING

Ship anchoring events in or adjacent to shipping fairways may be classified thus:

- Anchoring following machinery failure
- Anchoring to avoid collision
- Anchoring following collision

It may surprise some people to hear that the second class of event does not occur in practice. Ships avoid collision by altering course, not by anchoring. A ship attempting to anchor at speed will merely get her anchor gear torn away.

Ships anchor when their speed has fallen to a level where they have lost or are about to loose steerage way. The loss of speed may be deliberate following a collision, or may be the result of machinery failure. In either event there is a good chance that the ship can be steered to a point outside the fairway prior to dropping anchor.

The calculation of the probability of pipeline damage in the Great Belt due to ship anchoring following machinery failure is given in Reference A.

The calculation of the probability of pipeline damage due to ship anchoring following collision is given in Reference B.

It should be noted that these calculations refer to a separate assessment of pipeline vulnerability to anchor impact which is specific to a concrete-coated 30 inch pipe in the Danish Great Belt seabed soils, and calculations for other sizes of pipeline in other soils must be modified accordingly.

The calculations are also specific to the ship traffic characteristics.

3. SHIP GROUNDING

The development of a rational procedure for the evaluation of the risk of pipeline damage due to ship grounding proved even more important, and has been decisive for the selection of trenching depth in certain critical areas.

The procedure is somewhat more mathematical than that for anchor damage risk assessment. The initial calculation for the Danish Great Belt is set out in Reference C. The calculation has subsequently been slightly modified to reflect an adjustment of the pipeline trenching depth in the Great Belt to the East of Transit Route T.

This type of calculation is specific to ship traffic characteristics and seabed soil type and also to channel dimensions and shoal slope.

4. SUMMARY OF SHIP ACCIDENT RISKS IN THE DANISH GREAT BELT

The total level of ship accident risk for the Danish Great Belt Crossing as a whole is summarized in Table 1 below for a pipeline trenching depth of 1,0 metre from seabed to top of pipe. The figures relate to a single pipeline; they are doubled in the dual pipeline situation.

Table 1 - Ship Accident Risks for the Pipeline as a whole

	Anchoring Event following Engine Failure	Anchoring Event following Collision of 2 Ships	Ship Grounding Event	Total Ship Accident Events
Annual probability of accident event in Storebælt passage (Røsnæs-Omø) incl. all ship sizes	4,7	0,025	2,5	7,23
Whence expected number of events in 10 year period	47	0,25	25	72
Observed frequency of events per 10 year period	No information available	Only one event reported involving ships over 5000 DWT	10 ships of over 5000 DWT corresponding to 20 events for all ship sizes>500 BRT	
Annual probability & return period of damage (incl. rupture) to a single 30" pipeline in P.C. Route	$3,9 \times 10^{-3}$ 256 years	$>4,5 \times 10^{-5}$ <22.222 years	$2,74 \times 10^{-4}$ 3650 years	$4,22 \times 10^{-3}$ 237 years
Annual probability & return period of damage (incl.rupture) to a single 30" pipeline in Route 4	$<2 \times 10^{-3}$ > 500 years	$< 4,5 \times 10^{-5}$ >22.222 years	$2,74 \times 10^{-4}$ 3650 years	$2,32 \times 10^{-3}$ 431 years
Probability of damage incl. rupture) event during 30-year design life				
P.C. Route	0,12	0,001	0,01	0,13
Route 4	0,06	0,001	0,01	0,07

These risks are not distributed evenly along the length of the pipeline. The risk from anchor dragging following machine failure is concentrated in the Route T shipping channel. The effective width is regarded as 4 km; ships which still have some steerage way will aim to anchor outside this main lane; a study of the chart indicates that in Route 4 (the pipeline route finally selected) the risk will be spread over a total lateral distance of some 9 km, yielding a damage event probability of 2 x $10^{-3}/9$ or 2,22 x 10^{-4} per km per year.

The risk from anchor dragging following ship collision is distributed over a similar width, yielding 4,5 x $10^{-5}/9$ or 5,0 x 10^{-6} km per year.

The risk from ship grounding is concentrated in the first shoaling zones outside the main shipping channel. The critical areas are between the 14 m and 8 m depth contours. The total length between these contours, excluding the zones in Musholm Bugt which are protected from the main traffic by Slettings Grund, is some 2,5 km, i.e.: 1,5 km on the shoal east of Route T and 1,0 km on the steeper shoal towards the Fyn shore. This yields 2,74 x $10^{-4}/3,5$ or 1,1 x 10^{-4} per km per year.

These risk levels are set out in Table 2 together with the other general risks applicable to pipeline Route 4.

In Route 4 the total risk of serious damage or rupture, i.e.: events involving shutdown for repair, can be seen from Table 2 to be 4,3 x 10^{-3} per annum which is about twice the ship interference risk and is synonymous with a return period of 233 years. The probability of such an event within the 30 year design life of the pipeline is thus 12 percent for a single pipeline or 24 percent for a dual pipeline system.

Table 2 - Pipeline Route 4. Depth 1,0 m from seabed to top of pipe

Chainage	KP 0,5	1,5	8	12	17	21,0	23,5	28,4	29,4 total risk per year
Offshore activities	~ 10^{-5}	~ 10^{-5}	~ 10^{-5}	~ 10^{-5}	~ 10^{-5}	~ 10^{-5}	~ 10^{-5}	~ 10^{-5}	$2,9\times10^{-4}$
Anchoring after machine failure	~ 0	~ 0	$2,2\times10^{-4}$	$2,2\times10^{-4}$	~ 0	~ 0	~ 0	~ 0	$2,0\times10^{-3}$
Anchoring after collision	~ 0	~ 0	$5,0\times10^{-6}$	$5,0\times10^{-6}$	~ 0	~ 0	~ 0	~ 0	$4,5\times10^{-5}$
Ship grounding	$1,1\times10^{-4}$	0	0	0	0	$1,1\times10^{-4}$	0	~ 0	$2,7\times10^{-4}$
Anchoring intentional but position erroneous	~ 10^{-6}	~ 10^{-6}	~ 0	~ 0	~ 10^{-6}	~ 10^{-6}	~ 10^{-6}	~ 10^{-6}	$2,0\times10^{-5}$
Trawling	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0
Dropping of heavy objects	~ 10^{-6}	~ 10^{-6}	~ 10^{-6}	~ 10^{-6}	~ 10^{-6}	~ 0	~ 10^{-6}	~ 10^{-6}	$2,7\times10^{-5}$
External corrosion	$4,5\times10^{-5}$	$2,3\times10^{-5}$	$2,3\times10^{-5}$	$2,3\times10^{-5}$	$2,3\times10^{-5}$	$4,5\times10^{-5}$	$2,3\times10^{-5}$	$4,5\times10^{-5}$	$7,4\times10^{-4}$
Other external loadings	-	-	-	-	-	-	-	-	-
Total external loadings	$1,7\times10^{-4}$	$3,5\times10^{-5}$	$2,6\times10^{-4}$	$2,6\times10^{-4}$	$3,5\times10^{-5}$	$1,7\times10^{-4}$	$3,5\times10^{-5}$	$5,7\times10^{-5}$	$3,4\times10^{-3}$
Internal corrosion	3×10^{-5}	3×10^{-5}	3×10^{-5}	3×10^{-5}	3×10^{-5}	3×10^{-5}	3×10^{-5}	3×10^{-5}	$8,8\times10^{-4}$
Other internal loadings	-	-	-	-	-	-	-	-	-
TOTAL RISK PER KM PER YEAR	** $2,0\times10^{-4}$	$6,5\times10^{-5}$	* $2,9\times10^{-4}$	* $2,9\times10^{-4}$	$6,5\times10^{-5}$	** $2,0\times10^{-4}$	$6,5\times10^{-5}$	$8,7\times10^{-5}$	$4,3\times10^{-3}$

* These figures are unaffected by trenching depth

** These figures are highly sensitive to the local trenching depth

The highest level of risk per unit length of pipeline is seen to be 2,9 x 10^{-4} per km per year. This compares with a typical landline figure of 2,3 x 10^{-4} per km per year for all damage and leakage; the landline figure for serious damage only is probably an order of magnitude lower.

It should be noted that the risk level in the main channel, which is predominantly derived from anchor damage following ship machinery failure, is not sensitive to trenching depth, whereas the risk level on the shoals where grounding can occur is highly sensitive to the trenching depth assumption.

If the pipeline lies untrenched on the sea bottom, the risk level in the critical ship grounding zones is substantially greater than the generally accepted level.

5. PIPELINE DESIGN CONSIDERATIONS IN THE GREAT BELT

5.1 Choice of Trenching Depth

When these risk levels are compared with those generally prevailing for land and marine pipelines it can be concluded that, with a general trenching depth of 1,0 metre from seabed to top of pipe, the level of risk associated with ship accidents is within the range normally regarded as acceptable.

The question remains as to whether there are any reasonable steps which could be taken further to reduce or eliminate the ship accident risks.

The trenching depth required to eliminate all risk of pipeline damage due to anchoring is indicated in Table 3 below.

Table 3 - Anchor Penetration Depths

Ship Size	15,000 tdw	60,000 tdw
Anchor Weight	5,0 t	10.0 t
Penetration in Moraine Clay	2 m	3 m
Penetration in Mud	5 m	7 m

It is immediately apparent that trenching to "anchor safe depth" under these circumstances would be not only prohibitively expensive but impossible to achieve with ordinary construction methods.

In response to the continued concern of the Danish shipping authorities over the ship grounding risk immediately East of Transit Route T (at a location called Slettings Bank), however, DHI Marine Pipelines undertook a supplementary study which concentrated on the hazard to the ship's crew and the environmental pollution problem in the event of a tanker running aground on the pipeline (tankers represent approximately one half of the ship traffic in Route T).

This study built on a combination of the grounding risk computations referred to above with statistical accident data from Intertanko and oil slick movement patterns from the Danish Hydraulic Institute S. 21 current model for the Great Belt.

The conclusions of that report were that the installation of the proposed D.O.N.G. A/S gas transmission pipeline in the Great Belt on Route 4 with the trenching depths indicated in the Concept Proposal and assuming a single line is expected to yield the following risk increases:

- Existing risk of tanker disaster (i.e.: fire /explosion) in the Great Belt involving potential loss of life or serious injury to crew increased by 1,2 percent;
- Existing risk of oil pollution event in the Great Belt increased by between 0,065 percent and 1,3 percent.

The frequency of a tanker grounding event involving a single pipeline is estimated at once per 7.300 years. The frequency of a tanker larger than 40.000 DWT, i.e.: a crude oil carrier, grounding on the pipeline is estimated at once per 217.000 years.

It was nonetheless subsequently agreed with the Authorities that some risk reduction could be achieved within reasonable economic limits by trenching to a greater depth over a limited stretch of pipeline on the slope of Slettings Bank.

5.2 Number and Spacing of Pipelines in the Great Belt

Whereas the average repair time in the event of damage to a land pipeline is of the order of 1 or 2 days, the repair time in the event of damage to a 30 inch diameter pipeline in the Great Belt is estimated at upwards of a month (including dewatering and drying). A closure of this duration was found to be unacceptable in the context of security of gas supply to Zealand and Sweden. Therefore notwithstanding that the probability of failure is no worse than for other marine pipelines the consequences of such failure in terms of interruption of supply made it essential that the marine pipeline in the Great Belt be parallelled by a second pipeline.

5.2.1 Safety Distance between two Pipelines

In order to avoid damage to both pipelines from the same accident event the spacing between them must exceed the diameter of influence of any single event. The factors affecting choice of spacing include:

- Anchor dragging distance
- Stopping length of grounding ships
- Anchor spread from lay and bury barges
- Navigational considerations.

5.2.2 Anchor Dragging Distance

Under a controlled anchoring the ship will first drop anchor just before losing steerage way and starting to drift with the current. The mean anchor dragging distance in this situation will be less than 200 m even for the largest vessels passing the Great Belt.

The 200 m is the dragging distance related to areas with mud (gytja). The similar mean dragging distance in clay is less than 50 m. The thickness of the mud layer on the seabed in the Great Belt is generally less than 4 m. Boulder clay is found beneath the mud. In view of the large anchor penetration depths in mud most anchors will reach the boulder clay and the dragging distances will be less than those for deep mud.

The safe distance between two pipelines from the point of view of anchor damage is therefore of the order of 200 m.

5.2.3 Stopping Distance of Grounding Ships

When a vessel grounds on the seabed it will continue its forward movement and penetrate into the seabed. If the course of the ship in the grounding situation is parallel with the depth contours the ship will slide on the seabed for a considerable distance before its ultimate penetration is reached. This situation results in the largest stopping distances, but the smallest ultimate penetrations.

It can be shown that the minimum safe pipeline separation can be expressed as:

$$z = h_{GT} k \sin^{-\frac{1}{2}}\theta \cos\theta - x_t k \sin^{-1}\theta \cos\theta$$

where h_{GT} is the maximum depth of bite of the ship on grounding perpendicular to the shore, k is the cotangent of the seabed slope, and θ is the angle between the aberrant ship's course and the channel centreline.

The maxima of this function are tabulated below for x_t = 10 metre, k = 100, and a ship velocity of 12 knots.

Ship size (DWT)	Draught (metres)	Seabed soil	h_{GT} (metres)	z max. (metres)
50.000	12	clay	1,8	50
50.000	12	mud	3,8	350
150.000	17	mud	5,0	600

The nature of the input data is such that the accuracy of the results is no better than 50 percent. The safe pipeline separation in water depths of 8 to 12 metres should therefore be regarded as not less than 75 metres where the seabed is clay and 525 metres where the seabed is mud. The safe distance between the 12 and 17 metre depth contours, where mud prevails, must be regarded as not less than 900 metres.

5.2.4 Anchor Spread from Lay and Bury Barges

The spread of anchor positions perpendicular to the pipeline centreline typically extends from 100 m to 1,500 m. In order to avoid putting any restrictions on the lay and bury barge operations the distance between two pipelines should be either less than 100 m or more than 1,500 m. The spacings to be avoided are therefore those in the range of 100 to 1,500 m.

5.2.5 Navigational Considerations

From the point of view of the navigator of a vessel with machine failure, i.e.: a vessel considering dropping anchor, it is preferable that the two pipes either be located as close together as possible so that they can be regarded as a single crossing or alternatively be spaced several kilometers apart.

6. CONCLUSIONS

The example presented illustrates the role of safety analysis in development and modification of the engineering concept for a marine pipeline system crossing a navigational strait. It is shown that the systematic application of the calculation techniques developed in relation to the Danish Great Belt can aid the economic optimization of a capital project and at the same time establish confidence in the overall safety level.

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Ship/Platform Collision Risk in the U. K. Sector

Risques de collision dans le secteur britannique

Kollisionsrisiken von Schiffen und Offshore-Bauten

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SUMMARY

A major study of the risk of collision between passing vessels and offshore platforms is described. The study develops a new approach to platform risk estimates, based on the concept of definable shipping lanes. The results available to date indicate that the risk to certain platforms, near to major shipping lanes, is very high, whilst the risk to many others is sufficiently low not to be of significant concern.

RÉSUMÉ

L'étude décrit en détail les risques de collision entre les navires et les plates-formes situées au large. Cette étude propose une nouvelle méthode pour évaluer les risques des plates-formes en se fondant sur le concept de voies de navigation définissables. Les résultats montrent que les risques sont très élevés pour certaines plates-formes installées des grandes voies de navigation, tandis qu'ils sont moindres pour les autres plates-formes.

ZUSAMMENFASSUNG

Eine größere Untersuchung des Risikos von Kollisionen zwischen Schiffen und Offshore-Bauten wird beschrieben. Eine neue Annäherung an eine Risikoschätzung von Offshore-Bauten auf der Grundlage eines Konzepts festlegbarer Schiffsstraßen wird vorgeschlagen. Die Ergebnisse zeigen ein sehr hohes Risiko für bestimmte Plattformen, die nahe an Hauptschiffahrtsstraßen liegen, während das von vielen anderen ausreichend niedrig und nicht von großer Bedeutung ist.

1. INTRODUCTION

1.1 Background

Since drilling for North Sea oil and gas began in the mid 1960s, the possibility of ships colliding with offshore platforms or rigs has been of concern to both government and operators. Several studies have been undertaken by organisations in the UK and elsewhere to evaluate the risk of ship collisions and their consequences to both steel and concrete platforms [1,2,3]. During 1980 a review of these studies was undertaken on behalf of the UK Department of Energy by the Marine Technology Support Unit (MATSU) at Harwell [4]. This review concluded that the level of risk from ship collision might be sufficiently high to be of concern, but that there were a number of important omissions and discrepancies in the existing data. Hence the confidence which could be placed in the risk figures was too low for the Department's purposes. A recommendation for a broad based and more rigorous review of the collision hazard was made. This paper describes progress of the subsequent study, by consulting engineers Technica Ltd. to meet that recommendation.

1.2 Survey of available data

Before commencing work on a model of ship collisions, a survey was carried out of sources of relevant incident data. Various bodies were approached, such as HM Coast Guard, HM Customs, Trinity House, North Sea Pilots, and the UK Department of Energy (DOEN) Records Office. Of most use were the DOEN's records of safety zone infringements.

These records were examined in all the detail available, with a view to obtaining a picture of the collision hazards to offshore platforms by ships, and the circumstances in which such hazards occurred. The examination of these records highlighted the fact that a disturbing number of vessels passed within a few hundred metres, without altering course, without responding to VHF, or to signalling, marine radio, hailing, or actions by the standby vessel. In most cases, nobody could be seen on the bridge. For the purpose of this study, these vessels have been defined as "cowboy" vessels.

Numerically, Table 1 shows the results that emerged from this examination of UK safety zone infringements:-

Table 1 : Passing vessel infringements in the UK sector for the period 1973-1980

Number of passing vessel infringements:	53
Broken down as follows:-	
Definitely classified as "cowboy" vessels	13
Infringement Definitely due to other causes	16
Insufficient detailed information was available:	24

2. THE MODEL

2.1 The Approach Employed

The approach employed was to work from two hypothesis i) that the major cause of collision risk was from these "cowboy" vessels, and ii) that the traffic across the North Sea tended to follow particular routes that could be identified, and subsequently verified by experience and/or traffic surveys.

In developing a ship/offshore platform collision model, the objectives were set of ensuring that it was realistic, pragmatic and applicable to different sea areas. In other words, the model should accord with practical marine experience and the historical data applicable to the North sea.

In addition, the risk arising from vessels on these routes breaking down and then drifting onto the platform was examined. The parameters used in estimating the risk from this model is discussed below.

2.2 The Model Input Data

The important parameters required as input to the basic model are as follows:

1. Lane location, lane width, lane traffic, ship speeds.
2. Lane width, expressed as the probability of finding vessels on a cross section of the lane.
3. The percentage of cowboy vessels in any one lane.
4. Input concerned with vessels losing propulsion or steerage:- Details of expected course alterations that vessel would follow when using the platforms for navigational purposes; likelihood of engine or steering failure, stopping distances.
5. Input concerned with ability of platform personnel and nearby vessels to avoid loss of life from drifting vessel hazard.

For the purpose of quantifying the risk from passing vessels that appear not to be aware of the platforms, parameters 1, 2 and 3 are the only ones of concern and these are discussed below.

2.2.1 Shipping Lanes

Two areas have been selected for the study as the typical of likely high and low traffic densities. This enables a methodology to be developed to assess the risk of ship/platform collisions, in both absolute and relative terms, for which the traffic information is basic input.

The results for these two areas of a preliminary analysis of data on shipping movements, and on known origins and destinations of vessels crossing the North Sea, are given in Figure 1 for the Northern and Figure 2 for the Southern areas examined.

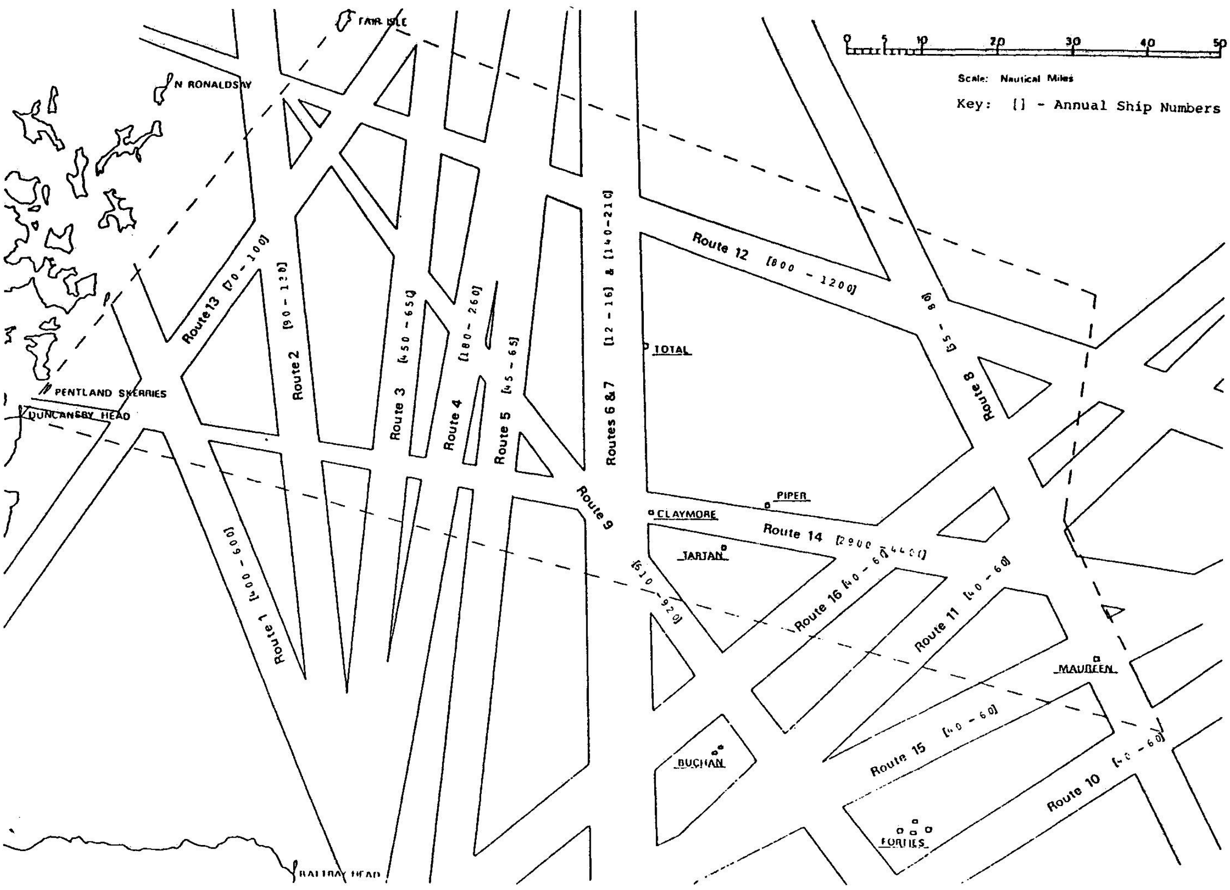

Fig. 1 Northern sector. Commercial shipping routes.

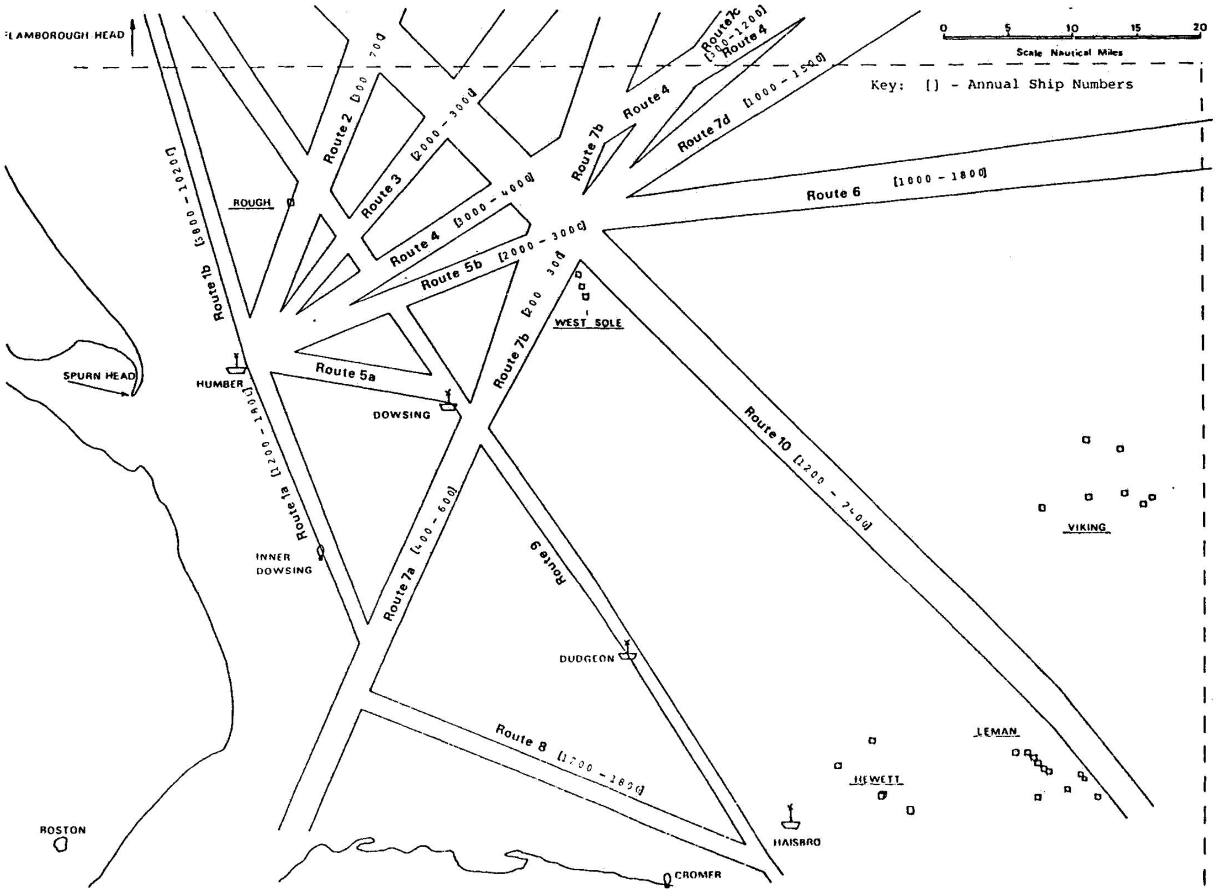

Fig. 2 Southern sector. Commercial shipping routes.

In verifying the location of the derived lanes for these two areas , the second stage was to seek the views of mariners experienced in North Sea navigation to establish and compare the main shipping routes identified, based on the navigation courses actually taken. To this effect, discussions were held with North Sea pilots and ship masters. The main courses or navigation routes were then drawn on Admiralty Charts of the areas in question. It immediately became apparent which oil and gas fields are adjacent to the commercial shipping routes.

For example, in the Southern Sector, the Rough and West Sole gas fields were seen to be adjacent to a crossing of routes between traffic bound to and from the Humber ports and the main UK East Coast routes. The Viking and Hewett fields are seen to be clear of the main commercial routes.

In the Northern Sector the Total, Claymore, Tartan and Piper fields were seen to be adjacent to a crossing area between the main Pentland Firth to Baltic route and the routes taken by large tanker traffic between Sullom Voe and points south. The Buchan, Forties and Maureen oil fields are seen to be relatively clear of the busier routes.

The further part of this stage was to ascertain some indication of the likely width of the routes taken. Again based on discussions with pilots and ship masters, these were found to vary according to location. In the relatively constrained routes of the Southern Sector, where navigation is restricted by the presence of shoals and sand banks, the indicated route widths varied between 1.5 and 5 nautical miles. In the Northern Sector, once clear of the coastline, the indicated route widths varied between 3 and 7 nautical miles.

In the Southern Sector, with permission of the Pilot Operations Manager, Humber Pilots, it was possible to make a limited radar survey from the Pilot Station at Spurn Head. From this survey it was possible to track the shipping, establishing the routes actually taken, their widths and the distribution of traffic across each route. The correlation with the routes indicated by the mariners was good, although the observations showed that the route widths were greater than indicated.

An analysis has been made of the distribution of traffic across each route and this indicates that the distribution is of Gaussian form. From the analysis of some 9 routes observed from Spurn Head it has been possible to establish the relationship between the standard deviation around the normal distribution and the route width.

2.2.2 Percentage of "Cowboy" vessels

It is now generally accepted that between 75% and 85% of all shipping accidents are due to human error where the human operator or navigator in this case does not adopt the procedure he has been trained to take, making an error of either commission or omission.

For the purpose of the collision risk model it is important to attempt to define the proportion of ships in the North Sea on which human error is likely to occur. For the purposes of this study such ships are termed "cowboy" ships as distinct from those ships which contravene traffic separation schemes, known as "rogue" ships, and those which do not comply with the construction, manning and equipment requirements internationally agreed in IMO Conventions, known as "sub-standard" ships.

The likely proportion of ships plying the North Sea which may fail to take appropriate action to avoid a collision with an offshore structure has not, to our knowledge, been the subject of investigation. Further, no one source of data is seen as suitable from which a confident expectation of the likely proportion may be determined.

A number of approaches have therefore been selected from which to view this problem. These include an assessment of the numbers of "sub-standard" and "rogue" vessels identified in other studies [5,6] as indicators of the likely upper bound of the "cowboy" population, and the consideration of the human failure rates contained within the series of Norwegian studies of causes and consequences of shipping accidents [7]. Consideration has also been given to the human failure rate in other occupational groups and finally, the subjective views of practising mariners and pilots have been sought.

The results from these approaches indicated a percentage of between 1-15% of the total shipping population as being likely "cowboys" with a bias towards the lower end of the band. In our view, we consider that a realistic range of the proportion of "cowboy" vessels to apply to the mathematical risk model should be between 1-5% of the total shipping population in any one lane.

3. RESULTS

3.1 Typical output

The output gives the drifting vessel and cowboy vessel collision probabilities for each shipping lane that can affect the platform, and then a grand total, summing the risks from each lane.

3.2 Typical results

The results are dependent primarily on one factor: the proximity of the platform to a major shipping route. Other factors, such as the lane width shape, the percentage of cowboy vessels and the minor shipping lanes, all contribute to the absolute level of risk, but not so significantly to the relative risk levels or to the sensitivity of the results.

For platforms in close proximity to the major lanes, the risk level is presently estimated to be of the order of 10^{-1} to 10^{-2} per year. This figure represents a high level of risk, well above most criteria of acceptability.

For platforms far from such shipping lanes, the risk is no longer dominated by cowboy vessels, and consequently the risk level is substantially lower, in the order of 10^{-5} per year. This risk level is comparable to or lower than other quoted figures for 'average' collision risk from passing vessels in the North Sea.

3.3 Substantiation of the results

These results are still preliminary, in that further work is currently under way to refine the shipping lane locations, the shipping traffic, the lane width and the percentage of cowboy vessels. If the results are, however, confirmed by this further work, then the results have important implications for North Sea safety.

3.4 Implications for North Sea operations

If the comparatively high risk figures for installations in close proximity to major shipping lanes are confirmed then the Department of Energy may need to consider the need for further regulations.

At the time of writing no decisions have been made in this regard, but requirements for fendering, surveillance and warning may have to be reviewed. Measures to meet requirements could be expensive and difficult to implement in view of the international nature of the problem and hence steps will not be taken lightly and, as with all regulations, only after consultation with the industries concerned.

4. CONCLUSIONS

i) A model for the risk of passing vessel collisions with offshore platforms in the North Sea has been developed that appears to be capable of providing platform specific estimates of the risk.

ii) The major preliminary results, which at the time of writing are not yet confirmed, are that

  a) The relative risk of collision for various installations are dependent primarily on their proximity to major shipping routes.
  b) Risks for most installations are low and present regulations are adequate to deal with them.
  c) Risks for the most vulnerable installations are unacceptably high and regulatory measures may have to be considered.

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Ship Collision against the Sunshine Skyway Bridge

Collision de bateaux contre le pont Sunshine Skyway

Schiffskollisionen mit der Sunshine Skyway Brücke

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SUMMARY

This paper outlines the methods used to perform a threat analysis of ship collisions with the new Sunshine Skyway bridge structure. A rational analysis of pier protection mechanisms and strength requirements of bridge piers was thus facilitated.

RÉSUMÉ

L'article traite de méthodes employées pour l'analyse de risque de collision des bateaux contre le pont Sunshine Skyway à Tampa, Floride. Cette analyse a facilité l'étude rationelle des mécanismes pour la protection des piles, et aussi la résistance requise pour les piles.

ZUSAMMENFASSUNG

Der Artikel berichtet über Methoden der Gefahrenanalyse von Schiffskollisionen mit der neuerbauten Sunshine Skyway Brücke. Die Analyse erleichterte das Verfahren zum Schützen der Brückenpfeiler und der Festigkeitsanforderungen an die Pfeiler.

1. GENERAL

Threat analysis [1] is the technique used to quantify, for any collection of assets, the degree of its vulnerability to damage or destruction by hypothesized threats. As it applies to the bridge problem, threat analysis involves the identification of the vulnerability of the bridge structure to ship collisions. Knowing this vulnerability enables the designer to determine the most appropriate and cost-effective measures to protect against the threats. This paper examines the three essential elements of threat analysis under the headings assets, threats and events, and mechanisms, and explains how the threat analysis findings were used to determine the cost-effectiveness of various pier protection systems for the Sunshine Skyway replacement bridge (Fig. 1). A 396.2 m section of the southbound span of the existing Sunshine Skyway bridge collapsed on May 9, 1980 when one of the anchor piers was struck by an empty 40,000 dwt phosphate carrier (see appendix). Thirty five lives were lost during the accident, as the result of motorists being trapped on, or driving off, the collapsed portion of the bridge.

2. ASSETS

An asset possesses two characteristics. First, it has some value to the organization which owns it; and second, it is capable of being threatened such that, under certain circumstances, its value is lost or damaged. Asset items for bridges are primarily the piers and spans which comprise the structure. While computationally possible to assign each bridge element as a separate asset category, it is generally desirable to group the piers and spans into larger assemblages which represent integrated sections of substructure and superstructure. Table 1 identifies one of the groupings utilized during the Skyway Bridge study. For each grouping of assets, the appropriate event cost parameters were determined.

3. THREATS AND EVENTS

The next phase of the analysis, after the assets have been categorized and evaluated, involves the identification of "threats" and "events".

3.1 Event Costs

Assets are subject to a variety of 'perils' which can cause them to lose value. 'Threats' are ordered pairs of the perils and the asset categories. For purposes of the analysis of the bridge, only one peril was recognized, that being vessel collisions. In the Skyway example, both the number of asset categories and consequently, the number of threats, is six. Each threat may be realized in a variety of different ways; each of these is called an 'event'. The analysis involved separate events in terms of seven classes of ships and barges based on size. Therefore, a potential total of 42 theoretical ship/pier collisions were possible. In fact, fewer were evaluated as it was impossible for certain vessel categories to impact the more distant piers because of reduced bay bottom depth in the area. For each event, it is necessary to determine "event cost" (EC) combining the evaluative parameters of the asset group involved. This EC value is a function of the independent variable, severity. In the analysis of the

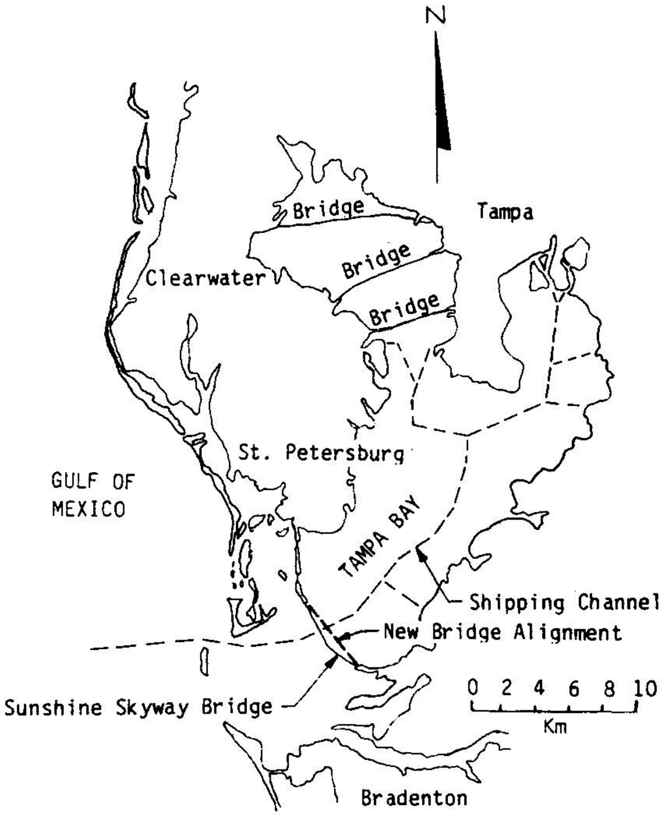

Figure 1. Project Location Map

	Annual Exposure ($1000) for Threat/Event Categories							
	SHIPS (GRT)				BARGES (GRT)			
Asset Categories	0 - 5,000	5 - 15,000	15 - 25,000	25 - 40,000+	0 - 5,000	5 - 15,000	15 - 25,000	TOTALS
Pier 1	47.9	115.9	111.7	42.4	125.4	261.6	38.3	743.2
Pier 2	55.6	127.6	131.8	40.3	44.5	298.6	43.9	742.3
Pier 3	11.7	29.2	31.2	10.6	9.5	70.5	9.9	172.6
Piers 4-6	19.2	45.8	52.2	18.4	15.6	112.7	17.4	281.3
Piers 7-16	17.6	45.6	45.1	14.9	15.3	109.1	16.0	263.6
Piers 17+	4.1	4.8	3.8	0.0	1.8	5.8	2.9	23.2
TOTALS	156.1	368.9	375.8	126.6	212.1	858.3	128.4	2,226.2

TABLE 1. Annual Exposure for Threat/Event Categories

Skyway Bridge, the following function is typical (Fig. 2):

$$EC = s \times PC; \text{ For } s < CR$$

and

$$EC = s \times [(1.4 \times (PC+SC)) + BC + H]; \text{ for } s \geq CR$$

with,

EC: The event cost
s: Severity
PC: Pier cost
SC: Span cost
BC: Business/Commerce Cost
H: Loss of human life cost
CR: Critical severity

The BC costs would include the cost of interruption of motorist access across the bridge due to bridge outage and the inconvenience costs to the port users in the event bridge wreckage were to block the shipping channel. The factor '1.4' is included to account for the fact that the replacement cost will be more expensive than the initial construction costs. An event cost must be developed for each asset category and for the variety of events which would involve that asset category.

3.2 Severity

The severity with which an event impacts an asset can be measured as the proportion of the total asset value affected, the length of time that the asset is denied to the organization, or both. Different events will most likely have different severities. For example, a 100,000 dwt ship will cause significantly more damage than a 10,000 dwt ship, all else being equal. The mathematical model distributes the severity according to a Poisson distribution, P(AS,s). This distribution is completely defined once a parameter termed the average severity (AS) is specified. The value will usually vary with every vessel collision event specified. Once an estimate of the average event severity is made, a distribution over severity is generated. The choice of the average severity unit (i.e., 10%, 20%, 30%, etc.) affects the shape of the distribution. Smaller units of average severity lead to more peaked distributions. Since severity has a limit of 100%, the Poisson distribution must be truncated after the first ten steps and the remaining probabilities proportionately adjusted. The average severity is determined by specifying the value which will generate the required probability of bridge collapse value for that particular event. Critical severity (CR) is defined as the step in the Poisson distribution in which a discontinuity occurs in the event cost formulae (Fig.2). For severity less than CR, the ship impact results in relatively minor damage and the expenditure of funds for repair of the structure. For severities equal to or greater than CR, the ship impact causes a total collapse of the bridge element and requires the expenditure of funds to replace the structure, in addition to the costs associated with loss of life and commerce. The same value of critical severity must be utilized for all events involving a particular asset category; in fact, in the analysis of the Skyway Bridge, a constant value for critical severity was used throughout.

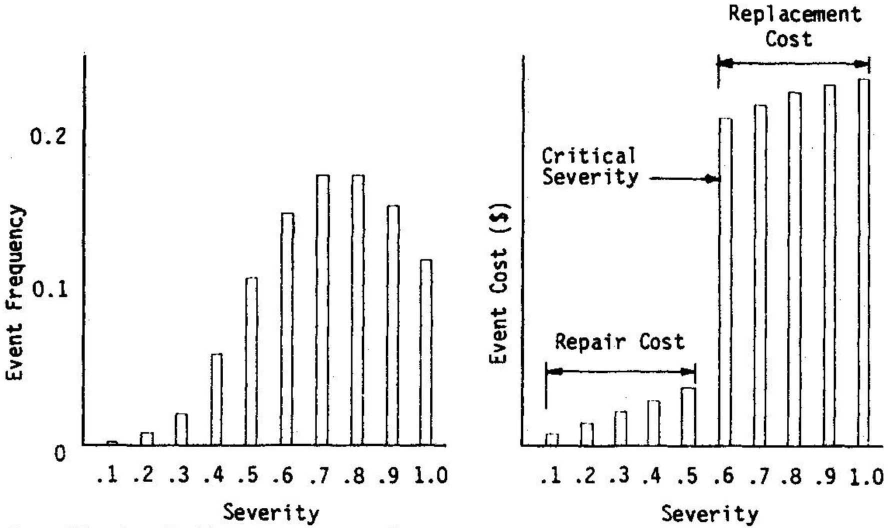

Figure 2. Typical Frequency - Severity - Cost Function Relationship

3.3 Exposure

For each event described, a value known as the exposure (EX) is calculated. Exposure is the expected value of loss to the owner of assets as a result of the event, and is usually expressed in dollars per year. Traditionally, the exposure of an event was derived by multiplying and event cost by its frequency. This is not really satisfactory, particularly because an event might have a wide variety of associated costs depending on a great many external circumstances. These extraneous conditions may be lumped together to yield not an average event cost, but a range of costs distributed against the severity of the event as explicitly defined above as event costs (Fig.2). The event exposure is calculated by multiplying the annual frequency of an event of any severity by the expected cost per event, itself generated using statistical techniques. In fact,

$$EX = AF \times \sum_{s} [EC(s) \times P(AS,s)]$$

Table 1 shows the results of this calculation for the Skyway Bridge.

3.4 Annual Frequency

The annual frequency of vessel collisions was estimated for each event category using the following equations:

$$AF = N \times PA \times PZ \times PG \times PE$$

and,

$$AFC = AF \times PC$$

with,

AF: Annual frequency of a ship collision with a bridge component.

AFC: Annual frequency of bridge component collapse due to ship impact.

N: Number of ships and barges in the various vessel categories which have the potential to strike a particular bridge element.

PA: Probability that a vessel is aberrant (out of the channel).

PZ: Probability that an aberrant vessel is located in a zone in front of a particular pier or pier grouping.

PG: Geometrical probability of a vessel striking a bridge component.

PE: Probability that the vessel master or pilot has not taken successful evasive action to avoid the collision.

PC: Probability of total collapse.

The number of ships and barges transiting under the bridge was estimated based on historical data available from maritime sources, and from making projections of future vessel traffic over the lifetime of the bridge structure. The number of vessels which can strike a pier or span will depend on the vessel gemetry, bridge clearances, and the water depth at the specific zone being analyzed.

The probability of aberrancy was determined for the Sunshine Skyway by analyzing the U.S. Coast Guard accident records for the Tampa Bay area. Knowing the number of accidents and the frequency of vessel traffic, the following probability values were developed:

PA (for ships) = 0.00013
PA (for barges)= 0.00022

As can be seen, the rate of barge accidents is almost twice that of ship accidents. The difference is probably a result of the mandatory pilotage requirements for ships in Tampa Bay, whereas there are limited pilotage requirements for barges. These values correspond closely to the value of PA = 0.0002 which was established by Fuji [2] on studies of ship collisions in Japanese waterways.

Values for PZ were estimated using a normal probability distribution. The median value was established at the centerline of the navigation channel. Based on historical worldwide ship collisions, a standard deviation of 457.2 m was chosen for the distribution. By statistical definition, 68.3 percent of all occurences occur within one standard deviation and 95.5 percent within two standard deviations. The collision zone for each pier or group of piers was defined as the distance between the span centerlines on the adjacent sides of the pier. Once the boundaries are known, a value of PZ can be computed based on the area under the normal distribution for that particular zone.

The geometrical probability that a vessel in the zone will hit a pier is a function of the width of the zone (ZW), the width of the horizontal clearance envelope from the pier(s) in the zone (LC), and the width of the ship (B). The following equation was utilized:

$$PG = [1- \frac{(LC-B)}{ZW}]$$

For the same zone and pier widths, a value of PG was calculated for each ship and barge category. A similar equation based on vertical clearance was utilized to compute PG values for an impact between bridge spans and vessel superstructures.

The probability that a ship pilot has not taken evasive action to avoid a collision (such as lowering the anchors, reversing engines, etc.) was modeled using the equation:

$$PE = e^{-(x/\sigma)}$$

with,

x: The distance from the channel centerline to the centerline of the collision zone.

σ: The standard deviation value utilized for the calculation of PZ.

e: The base of the natural logarithm.

The equation models the observed action of piloting, where the closer an abberant vessel is to the channel, the less probable it is that the pilot is aware that he is aberrant; and similarly, the further away from the channel the aberrant vessel becomes, the probability increases that the pilot is aware that he is out of the channel and will take evasive action to avoid the collision.

The probability of bridge collapse varies for each event. It is a function of the vessel size, configuration, speed, direction, mass and the nature of the collision. It is also a function of the stiffness of the bridge pier (or span) to resist lateral loads. The less the lateral design load of a bridge pier, the greater the probability of collapse, and vice versa. The following relationship was developed to compute PC:

$$PC = (A)^{H/PM}$$

with,

H: The ultimate bridge element lateral design force (MN).

PM: The average bow collapse force of a vessel (MN).

A: A constant expressing the estimated probability of collapse when H = PM.

Values for PM were estimated using a modified form of Woison's [3] equation in the form:

$$PM = .333 \sqrt{dwt} \quad (MN)$$

with,

dwt: The deadweight tonnage (LT).

The modification revised the constant in front of the radical from the original .440 to .333 and also removed the +50 percent spread estimated by Woison. The revisions were determined by calibrating Woison's equation to generate the forces calculated in the ship collision of the M/V Gerd Maersk with the Newport Bridge in Rhode Island, U.S.A., on February 19, 1981 [4].

A value of A = 0.10 was utilized for the Skyway project, and expresses the estimated number of times a vessel collision would cause the collapse of a pier, given that the vessel impact and pier resistance forces were equal. This represents one out of every 10 collisions causing collapse, with the remainder causing only slight damage to the bridge.

The annual frequencies of all events involving each asset category are indicated in Table 2. Those events involving bridge collapse are separated for all collisions, and the return periods (inverse of annual frequency) are shown. It is interesting to note that whereas Pier 2 (north and south anchor pier) is struck less often than Pier 1, the frequency of Pier 2 collapse is greater. This resulted from the lateral design load of Pier 2 being three times less than that for Pier 1.

Pier No.	Bridge Collision	Bridge Collapse
1, N & S	14	157
2, N & S	31	93
3, N & S	56	162
4-6, N & S	33	96
7-16, N & S	45	88
17+, N & S	500	943
All Piers	6	22

TABLE 2. Bridge Collision and Collapse Return Periods (Years) for the unprotected

The probability of total collapse can also be visualized as the area under the Poisson distribution for all values equal to, or greater than, the critical severity for a particular specified average severity value. This permits the calculation of AS as that which satisfies the equation,

$$\sum_{s=CR}^{\infty} P(AS,s) = PC$$

4. MECHANISMS

Once the events which seem possible have been identified and the quantification of these events has been completed, exposures for each are determined. The exposures of all events within a given threat are added to estimate the threat exposure. Threat exposures are then ranked to determine areas of greatest vulnerability. Once this is done, protection mechanisms are developed to reduce those areas of greatest vulnerability.

There are three different ways by which protection mechanisms impact the analysis: (1) by reducing the overall probability of an event, (2) by altering the severity distribution (more events of a less severe nature), and (3) by reducing the costs of events of whatever severity. The Skyway study investigated the use of physical protection devices such as artificial islands, large diameter dolphins, changes to bouy and range marker locations, electronic navigation systems, and a motorist warning system. The latter would entail a warning system to motorists which would stop all vehicular traffic from driving across the bridge. Table 3 indicates the results of the analysis for the protection mechanisms. Each protection mechanism has associated with it an expected lifetime, an initial cost, maintenance cost and resale value, in addition to its impact on reducing the bridge vulnerability.

Asset Categories	Initial Exposure ($1000)	Revised Annual Exposure ($1000) for Pier Protection System Alternatives								
		Dolphins (4 piers)	Dolphins (6 piers)	Dolphins (12 piers)	Islands (4 piers)	Islands (6 piers)	Islands (12 piers)	Standard Navigation Improvements	Electronic Navigation System	Motorist Warning System
Pier 1	743.2	0	0	0	0	0	0	457.7	616.2	667.5
Pier 2	742.3	0	0	0	0	0	0	460.4	602.2	677.7
Pier 3	172.6	172.6	86.3	86.3	172.6	0	0	107.9	138.6	153.2
Piers 4-6	281.3	281.3	281.3	140.6	281.3	281.3	0	173.7	226.4	252.3
Piers 7-16	263.6	263.6	263.6	263.6	263.6	263.6	263.6	161.2	214.2	241.8
Piers 17+	23.2	23.2	23.2	23.2	23.2	23.2	23.2	17.0	20.4	21.8
TOTALS	2,226.2	740.7	654.4	513.7	740.7	568.1	286.8	1,377.9	1,818.0	2,014.3

TABLE 3. Revised Annual Exposure for Pier Protection System Alternatives

5. COST-EFFECTIVENESS ANALYSIS

In order to provide analytical substantiation of the economic feasibility of bridge protection mechanisms, and to provide a measure for comparing protection alternatives, a cost-effectiveness analysis (CEA) was accomplished. The CEA consists of the computation of yearly costs and benefits associated with a protection mechanism over a fixed term. The costs include construction, maintenance, and operation costs for the mechanisms. Benefits are represented by any reduction in exposure costs (EX) which the mechanism can be shown to provide. The future costs and benefits are converted to present values with standard discounting procedures, based on assumptions for inflation and interest rates. From these present values of costs and benefits, a series of indicators of economic desirability are derived. They include benefit/cost (B/C) ratio, present value of net benefits, internal rate of return, and payback period. Table 4 depicts typical results of the CEA procedures.

Pier Protection Alternative	Initial Cost	Annual Maintenance	Expected Lifetime (Years)	Benefit/Cost Ratio (5% Discount)
Dolphins - 4 Piers	$17,230,000	$23,000	35	3.48
Dolphins - 6 Piers	20,022,000	26,880	35	3.32
Dolphins - 12 Piers	28,603,000	38,400	35	2.26
Islands - 4 Piers	20,440,000	7,000	50	4.59
Islands - 6 Piers	24,080,000	14,000	50	4.33
Islands - 12 Piers	34,240,000	28,000	50	3.54
Standard Navigation Improvements	1,000,000	6,000	20	17.33
Electronic Navigation System	600,000	8,000	10	6.49
Motorist Warning System	220,000	5,000	10	4.26

TABLE 4. Benefit/Cost Ratios for Pier Protection Alternatives

6. CONCLUSIONS

The methodology adopted to analyze the threats and to determine the cost-effectiveness of proposed pier protection devices for the Sunshine Skyway was found to be satisfactory by the Florida Department of Transportation and the Federal Highway Administration, U.S.A. The analysis indicated that a high degree of vulnerability of the bridge would exist if it were left unprotected, so that some form of pier protection would be justified.

The application of the threat analysis techniques summarized in this paper must be approached with some caution. As with any form of statistical analysis, accuracy of results is dependent on the extent of knowledge and research utilized in the formulation of the important input assumptions for the model, and the extent of the experience of the organization using it.

The use of the approach as a design tool to determine optimum span length, vertical clearances, and pier strengths to minimize the vulnerability of the bridge to ship collisions has not been fully explored; however, it appears that this can be a valuable aspect of the methodology.

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APPENDIX

Photograph of the M/V Summit Venture accident with the existing Sunshine Skyway Bridge on May 9, 1982.

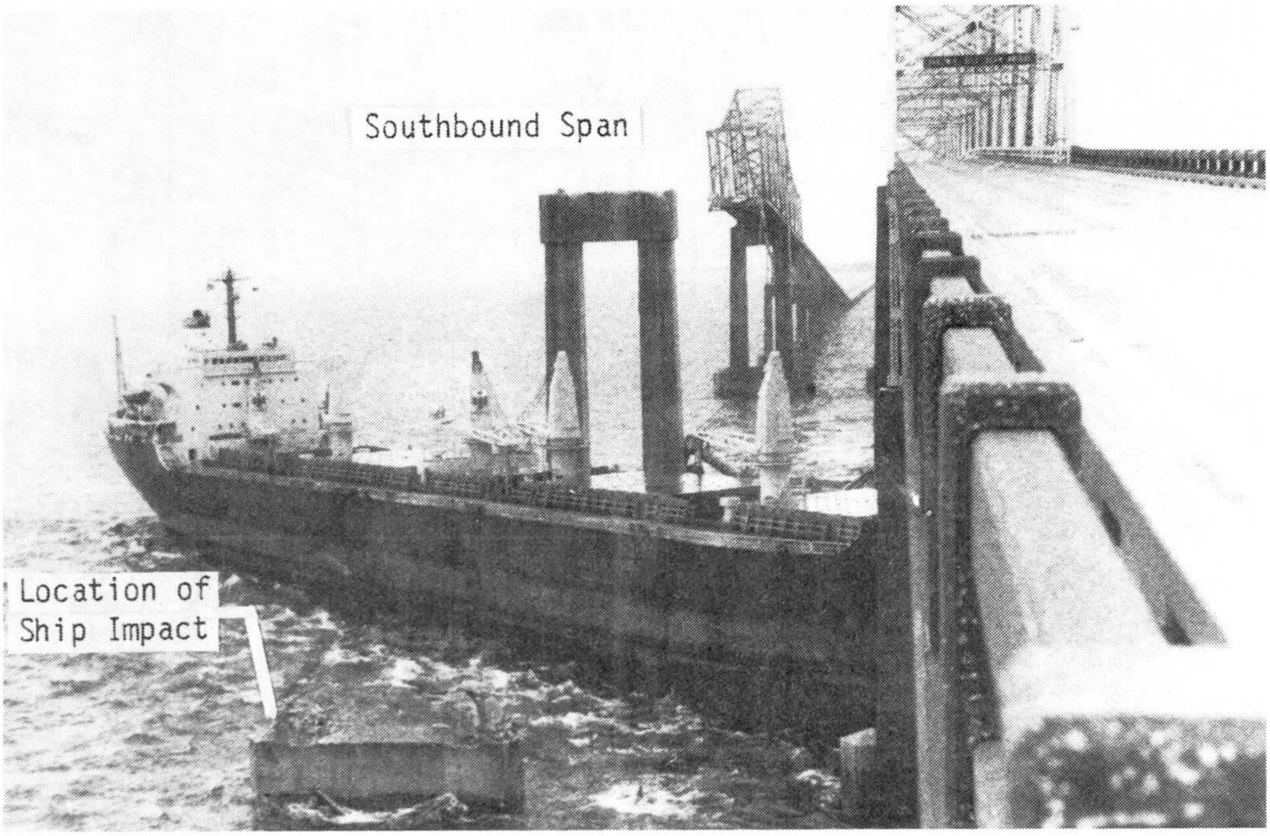

Photo: T. P. O'Neill, Courtesy Shackleford, Farrior, Stallings & Evans, P.A.

Platform Collision Risk on the Norwegian Continental Shelf

Probabilité d'une collision de plate-forme en Mer du Nord

Kollisionsrisiko mit »Offshore«-Bauten in der norwegischen Nordsee

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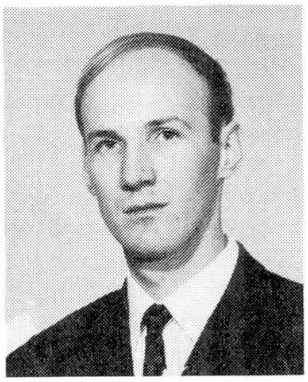

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SUMMARY
This paper suggests a model for the estimation of the ship-platform collision probability. The model is applicable in the risk-assesment phase of the planning and design of offshore installations. An analogy with ship accidents is utilized in the model. The findings from a survey of the marine traffic in the Norwegian part of the North Sea are summarized. The collision probabilities have been estimated for the Statfjord and Ekofisk fields.

RÉSUMÉ
Cette publication présente un modèle de probabilité d'une collision entre un navire et une plate-forme. Ce modèle peut servir pendant la phase d'évaluation de risques de constructions en mer. Ce modèle fait l'analogie avec des accidents de navire et présente le résumé des résultats des observations de la circulation dans la part norvégienne de la Mer du Nord. Les probabilités de collision ont été estimées pour les gisements de Statfjord et de Ekofisk.

ZUSAMMENFASSUNG
Diese Arbeit schlägt ein Modell für die Berechnung der Kollisionswahrscheinlichkeit Schiff-Plattform vor. Das Modell ist für Planung und Entwurf von Offshore-Bauten der Risikoanalyse angepaßt. Das Modell setzt eine Analogie mit Schiffsunfällen voraus. Die Ergebnisse einer Studie des Seeverkehrs in den norwegischen Nordseegebieten werden erläutert. Die Kollisionswahrscheinlichkeiten auf Statfjord und Ekofisk sind näher untersucht worden.

1. INTRODUCTION

Platform installations in the North Sea are exposed to a number of risk phenomena. One of these is the collision with a vessel or other mobile unit. The marine traffic is usually structured as follows: Visiting vessels, nearby traffic and passing ships. This paper is confined to the probability of collision between a passing vessel and a platform. Because of speed and displacement the collision with a passing vessel represents one of the greatest accidental loads to the platform. So far, only one collision of this type has been reported [1].

National Maritime Institute in Great Britain have done pioneering work in the field of platform collision risk estimation. It is referred to reports by Anonymous [2], Batchelor, Chalk and Lewison [3] and Barratt [4]. The models for collision probability is largely based on analogies with the ship-ship collision scenario. The traffic exposure have been studied through various forms of surveys. Similar models have been suggested by Goodwin and Kemp [5].

Accident phenomena as ship-ship collision, grounding and stranding are better known than the ship-platform collision. This is both in terms of models and empirical data. We shall only briefly list some of the contributions in the field of marine traffic research: Oshima and Fujii [6], Fujii and Shiobara [7], Fujii and Tanaka [8], Fujii, Yamanouchi and Mizuki [9], Lewison [10], Dare and Lewison [11], Lewison [12], Macduff [13], Van der Tak and Spaans [14], Kwik and Stecher [15], Kwik [16], Kwik [17], Krappinger [18], Krappinger [19], Chen [20].

The analysis and understanding of the failure processes that may lead to platform collisions are by no means complete. One reason for this is the simple fact that these collisions are very rare events. We have for instance not been witness to collisions between merchant ships and platforms in the North Sea to this day.

Experience from groundings and ship-ship collisions further indicate that this type of casualty has a rather complex nature. The main components of the collision-process are following phases: Exposure, initiation, causation, structural and system damage and development of consequences. The actual casualty may take one of a number of potential patterns or sequences.

It is further a situation or scenario for a collision. This is the set of passive factors such as the fairway and the platform located in the fairway. The situation is further characterized by its exposure to weather and sea.

The initiating element is the traffic near the platform. Under normal conditions this traffic will pass without any incidents. The degree of risk or probability that this traffic can lead to collisions may be related to factors as traffic density, ship characteristics and symptoms like the number of infringements of regulations applying to the traffic.

The most complex and less understood component is the causation process. This is so because the accident often develops as an interaction between organizational, human, technical and ergonomic factors. The interaction process is both timedependent, multidimensional, dynamic and stochastic in its nature. The MORT system Johnson and Lowman [21] was developed as framework for the analysis of such accident phenomena. The author of this paper has studied the causal factors of groundings and ship-ship collisions. See the report by Karlsen and Krisitansen [22]. Another interesting approach is the socalled Task Analysis. See Smith et al [26].

The rest of this paper will be devoted to the estimation of platform-collision probability. The model that is suggested is based on concepts familiar in traditional marin traffic research. It is hoped that the model will contribute to a more unified analysis of casualties of the impact-type.

2. ACCIDENT PROBABILITY

2.1 Model concept

The model that will be presented in this paper is applicable both to ship accidents and ship-platform collisions. The model scenario is as follows. A limited fairway-section is given. This fairway may have obstructions like coastlines, shoals, offshore platforms and ship traffic. A vessel enters the fairway section and may loose control during the passage due to navigation error, mismanouvre or system failure. Loss of control is assumed to give the ship a linear course with random heading. The ship may then hit one of the obstructions in the fairway. The probability of such an impact is a function of the fairway-geometry and ship-kinematics.

Assuming that a fairway segment is exposed to N ship passages, the expected number of accidents of a certain kind is given by:

$$C = N \cdot P \cdot I \cdot K \qquad (1)$$

where the probability of loss of control is taken as a function of distance sailed, D, and the failure intensity, μ:

$$P = \mu \cdot D \qquad (2)$$

The expected number of impacts per passage assuming non-control, I, is a function of the accident scenario. The most common scenarios will be described in the following paragraphs.

The visibility is viewed as the most dominating external parameter. The model takes account for visibility by means of the factor K.

2.2 Grounding, stranding

The situation where a ship may ground in a straight fairway is depicted in figure 1. It is easy to show that the expected number of groundings per passage given a random course is given by:

$$I_G = \frac{B+C}{W} \qquad (3)$$

The numerator expresses the sum of ship breath and effective cross-section of the shoal. Studies by Fujii, Yamanouchi and Mizuki [9] indicates a probability of loss of control in the range of:

$$P_G = 2 \cdot 10^{-4} \qquad (4)$$

The stranding scenario is also shown in figure 1. Assuming a random course ahead we get as follows:

$$I_S = \frac{\alpha}{\pi/2}$$

This expression is based on the average position during the passage of the fairway distance D. Using a series-approximation we get the expression:

$$I_S = 1 - \frac{2 \cdot W}{\pi \cdot D} \qquad (5)$$

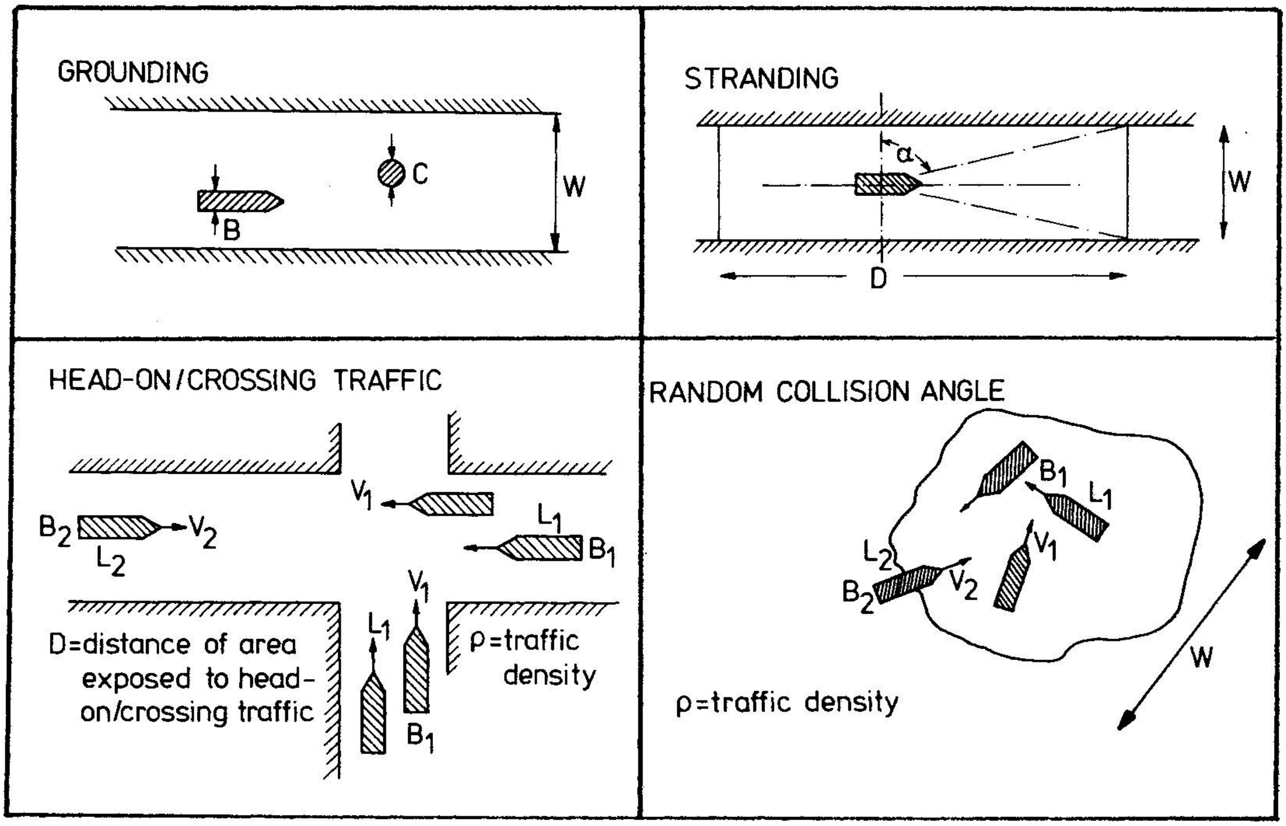

Figure 1. Ship accident scenarios

Fujii, Yamanouchi and Mizuki [9] has also estimated the loss-of-control intensity for strandings:

$$\mu_S = 2 \cdot 10^{-5} \text{ failures/n.mile} \qquad (6)$$

2.3 Ship-ship collisions

Figure 1 describes the most typical collision scenarious: Head-on, crossing and random traffic. We assume that own ship (indexed 2) is exposed to the traffic in a fairway (indexed 1). The fact that both ships may contribute to a collision gives following modification of the basic model (equation 1):

$$C = 2 \cdot N \cdot P \cdot I \cdot K \qquad (7)$$

Assuming straight traffic flows it is a rather simple task to develop expressions for the expected number of collisions per passage for own ship:

Head-on : $$I_{CH} = (B_1+B_2)(V_1+V_2)\ \frac{D}{V_2}\cdot\rho \qquad (8)$$

Crossing: $$I_{CC} = ((L_2+B_1)V_1 + (L_1+B_2)V_2)\ \frac{D}{V_2}\cdot\rho \qquad (9)$$

Length and breadth of ship are expressed by L and B, and speed by V. The models are also functions of distance, D, and traffic density, ρ.

Chen [20] has suggested a model for a random traffic pattern. Assuming average values for main ship dimensions and speed Kristiansen [23] has suggested:

$$I_{CR} = (\frac{4}{\pi}\cdot L + 2\cdot B)\ W\cdot\rho \qquad (10)$$

Analysis of studies by Chen [20] and Lewison [12] indicates loss-of-control failure intensities in the following range:

Situation	μ(failures/n.mile)
Head-on	$3{,}0\cdot 10^{-5}$
Overtaking	$1{,}5\cdot 10^{-5}$
Crossing	$1{,}5\cdot 10^{-5}$
Random crossing	$2{,}0\cdot 10^{-5}$

2.4 Reduced visibility

The values for loss-of-control intensity, μ, quoted in the preceeding paragraphs is based on the visibility conditions prevailing in Dover. The visibility may be described with following parameter:

$$VR = 330\cdot t_1 + 20\cdot t_2 + t_3 \qquad (12)$$

where t_i expresses the relative occurence of visibility code i. Following values have been estimated by Lewison [10] for Dover:

Code:	i	1	2	3
Range		<200 m	200m-4km	4 km<
Occurence:	t_i(%)	0,76	4,96	94,28

The correction factor for Dover can then be computed:

$$VR_D = 4{,}44$$

This means that the expected number of accidents in Dover is more than four times as high as clear weather conditions would suggest.

We are now able to take account for the visibility, expressed by VR, in other waters:

$$K = VR/VR_D \qquad (13)$$

The model is in general also confirmed by Fujii and Yamanouchi [24].

2.5 Ship-platform collisions

As already pointed out the probability of collision between ship and platform can not be based on empirical data. We will now propose a model which is the analogue to the ship-accident scenarios presented in the preceeding paragraphs.

Figure 2 describes a situation where a platform is exposed to a colinear traffic flow of ships. This is identical to the situation where the platform "moves" with the same speed, V, relative to the "stationary" ships. During a time period, T, following area is exposed to collisions:

$$A = (B+E) \cdot V \cdot T \qquad (14)$$

Assuming a traffic density, ρ, we get following expression for the expected number of ship-platform collisions:

$$C = T \cdot P_{PC} \cdot (B+E) \cdot V \cdot \rho \cdot K \qquad (15)$$

In the absence of any estimate for the probability of loss of control in the vicinity of a platform, following average value for ship accidents is suggested:

$$P_{PC} = 2 \cdot 10^{-4}$$

The interval of uncertainty should at this stage of knowledge at least be: $1 \cdot 10^{-4}$ to $3 \cdot 10^{-4}$.

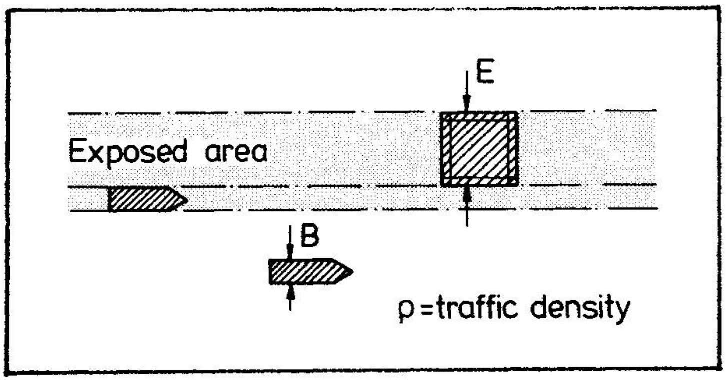

Figure 2. Ship-platform scenario

3. EXPOSURE TO PASSING TRAFFIC

3.1 Coast Guard Data

The marine traffic in the Norwegian economic zone is observed on a near continous basis by Coast Guard vessels and airplanes. Coast Guard observation data have been analysed by Laheld [25] and Gunnersen [26]. These data are the basis for the collision probability estimates in this paper. Figure 3 shows the average merchant ship traffic density (ships per 1000 nm^2) for the period 10.09.1981 - 21.07.1982.

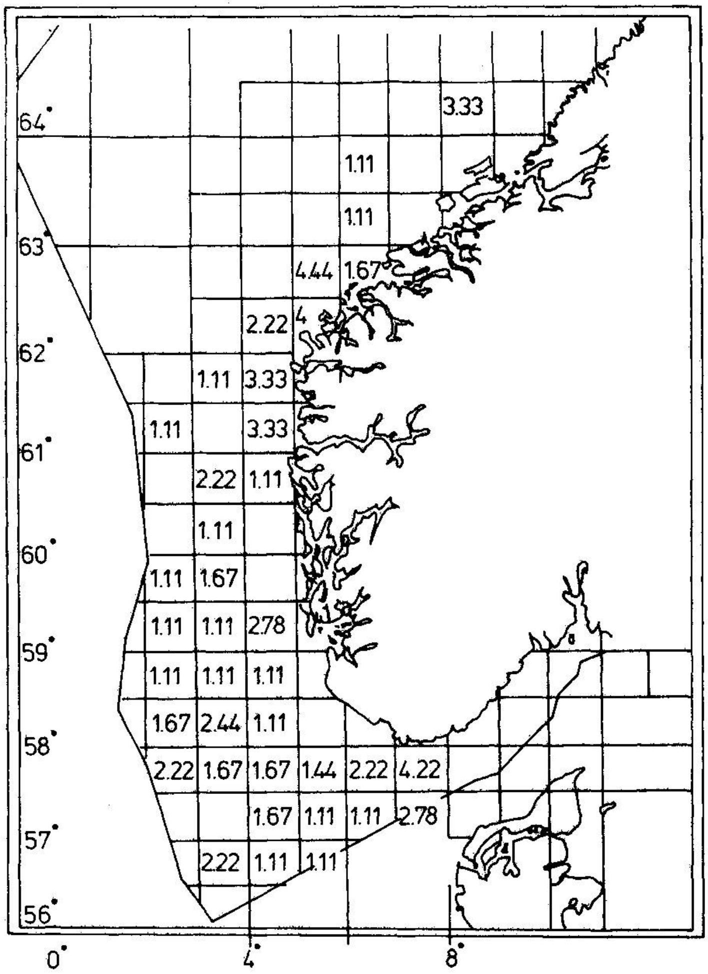

Figure 3. Merchant ship traffic density.
(Ships/1000 nm^2). 10.09.81-21.07.82.
Monthly air patrol observations.

3.2 Traffic desity

The traffic density of merchant and fishing vessels have been estimated for the Norwegian economic zone south of 62°N. These estimates were based on monthly air observations in the period January 1981 - July 1982. A rate of detection of 70% was assumed [2]. The average traffic density is $2{,}08 \cdot 10^{-3}$ ships/km^2 which compares well with $1{,}95 \cdot 10^{-3}$ based on NMI-data [2]. Estimates for Statfjord and Ekofisk are shown in table 1.

Table 1. Traffic density in the Norwegian economic zone (ships/1000 km^2)

Area	Fishing vessels	Merchant ships	Total
South of 62°N	1,46	0,62	2,08
Statfjord	0,77	0,40	1,18
Ekofisk	0,56	0,80	1,36

At Statfjord merchant ships represent 34% of the traffic whereas it comes to 59% at Ekofisk.

3.3 Traffic near installations

The traffic density estimates are based on observations in localities of 900 nm^2. It has been shown in a number of studies that a considerable part of the marine traffic will avoid potential hazards in the fairway. This means that the traffic density in the vicinity of an installation is lower than the density for the corresponding locality. Based on local surveys for Forties and Statfjord [3] and [27] the reduction factor for traffic inside a 12 nm annulus is conservatively estimated to 30%. This gives following merchant ship density near installations:

- Statfjord field: $0{,}12\cdot 10^{-3}$ ships/km^2
- Ekofisk field: $0{,}24\cdot 10^{-3}$ "

4. COLLISION PROBABILITY

4.1 Expected number of collisions with merchant ships

In order to estimate the number of collisions in a period platform dimensions, traffic speed and visibility must be established. The assumed characteristics for Statfjord and Ekofisk are summarized in table 2. Both a single platform and the whole field are studied.

Table 2. Model paramtres

Field		Statfjord	Ekofisk
Collision diameter B+E (km)	Platform	0,090 1)	0,203 2)
	Field	0,326	1,857
Visibility: K		0,88	1,25
Ship speed (m/sec)		5,2	5,2

1) Condeep-platform 2) Albuskjell 2/4 F-PDQ

The expected number of collisions with merchant ships in one year has been computed by means of formula (15). The results are shown in the first line of table 3. It appears that the expected number of collisions for the Albuskjell 2/4 F is more than 6 times as high as for a Condeep platform at Statfjord. Further, the estimates indicate that the expectancy of collision at Ekofisk is more than 16 times as high as for Statfjord.

4.2 Collision probability

By assuming that collisions can be described by a Poisson-distribution, we are able to estimate the probability that a collision will happen in the course of the field-life. From table 3 it appears that the probability of a collision at Statfjord in 30 years is 28%. This must be viewed as an alarming high figure. The implication of the model is further that a collision at Ekofisk in the course of 15 years is almost sure to happen (94% probability).

Table 3. Expected number and probability of collision

Platform or field	Condeep	Statfjord	Albuskjell	Ekofisk
Collisions per year: C	$3{,}1\cdot 10^{-3}$	$1{,}1\cdot 10^{-2}$	$20{,}0\cdot 10^{-3}$	$18{,}3\cdot 10^{-2}$
Production period (years)	30	30	15	15
Probability of at least one collision	0,088	0,28	0,26	0,94
Operation period (years)	5		10	
Probability of no collision	0,98		0,82	

The above given conclusions may perhaps be viewed as contradicted by our experience so far, looking to the fact that no collision has happened to this day. A closer look, however, shows that this argument should be rejected. The probability of not having a collision in say 5-10 years has been computed by means of the model. A collision with a Condeep-platform in 5 years is not a likely event (98%). Even a collision with an Albuskjell platform type in 10 years is not very probable.

5 CONCLUSIONS

The model presented in this paper indicates that a collision with a platform in the Norwegian zone is much likely to happen in the course of a field's life. The conclusion is, however, based on experience from ship accidents and limited traffic data.

It is recommended further research on the modelling of platform collisions and more extensive traffic surveys. This will enable us to give better estimates of the collision probability.

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