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Ship Collision Risk Assessment for Bridges

Evaluation des risques de collisions de navires avec des ponts

Abschätzung der Risiken in bezug auf Zusammenstöße von Schiffen mit Brücken

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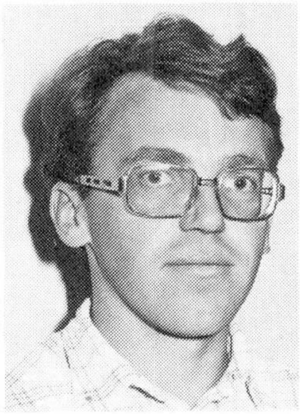


Ole Damgaard Larsen, born 1942, graduated from the Technical University of Denmark as a civil engineer in 1965. His professional work has mainly been within the fields of bridges and structural engineering. He has been involved in ship collision studies in connection with several bridges in Denmark and abroad and his experience covers statistical aspects as well as design aspects.

SUMMARY
The recurring serious ship collision accidents make it clear that this risk must not be disregarded when designing bridges crossing navigated waters. However, this design parameter creates problems for the designer because piers of normal design cannot withstand forces of the magnitude in question. For many bridges, an absolutely safe solution will be prohibitively expensive. For major bridges it is thus reasonable to treat the problem of ship collision by means of a probabilistic appraoch, since this allows us to weigh the risk level against the construction costs on a rationel basis. This paper describes the structure of a risk assessment model and discusses the many parameters of importance, with reference to investigations carried out in connection with major bridge projects .

RÉSUMÉ
De graves accidents impliquant la collision de bateaux avec des ponts se produisent périodiquement et il est bien évident que ce genre de risque ne doit pas être négligé lors du projet de ponts enjambant des voies d'eau navigables. Ce paramètre de projet suscite toutefois de sérieux problèmes pour l'ingénieur, vu que des piliers normalement conçus ne sont pas en mesure de résister aux énormes forces en question. Pour la construction de nombreux ponts la solution offrant une sécurité absolue se révèle particulièrement onéreuse. Il est donc tout à fait raisonnable de résoudre le problème des collisions de bateaux et d'équilibrer le taux de risques par rapport aux coûts de construction sur une base rationnelle , soit à l'aide de calculs de probabilité. L'article décrit l'établissement d'un modèle d'évaluation des risques encourus et traite les paramètres les plus importants en se référant aux recherches conduites en relation avec les principaux projets de ponts.

ZUSAMMENFASSUNG
Immer wiederkehrende Schiffszusammenstöße machen deutlich, daß ein solches Risiko beim Bau einer Brücke, die schiffbare Gewässer überquert, nicht übersehen werden darf. Dennoch führt dieser Bauparameter für den Entwerfer zu Schwierigkeiten, da normal gebaute Brückenpfeiler nicht imstande sind, derartigen Kräften standzuhalten. Für viele Brücken erweist sich diejenige Lösung, die eine absolute Sicherheit gewährleistet, als unerschwinglich. Bei Großbrücken ist es daher sinnvoll, die eventualität eines Schiffszisammenstoßes mit Hilfe einer Wahrscheinlichkeitsrechnung zu lösen, die ein Abschätzen des Risikoumfanges unter Bezugnahme der eigentlichen Baukosten auf rationaler Ebene ermöglicht. Dieser Artikel beschreibt die Struktur eines Risikoabschätzungsmodells und erläutert zahlreiche wichtige Parameter, unter Bezugnahme auf die in Zusammenhang mit Großbrücken durchgeführten Untersuchungen.

1. INTRODUCTION

The recurrence of serious ship collision accidents - one or two every year - highlights the fact that the risk of ship collisions must not be disregarded when designing bridges crossing navigated waters.

However, this new design parameter creates problems because piers of normal design cannot withstand forces of the magnitude in question. For many bridges, an absolutely safe solution will be prohibitively expensive. This fact is illustrated in fig. 1.

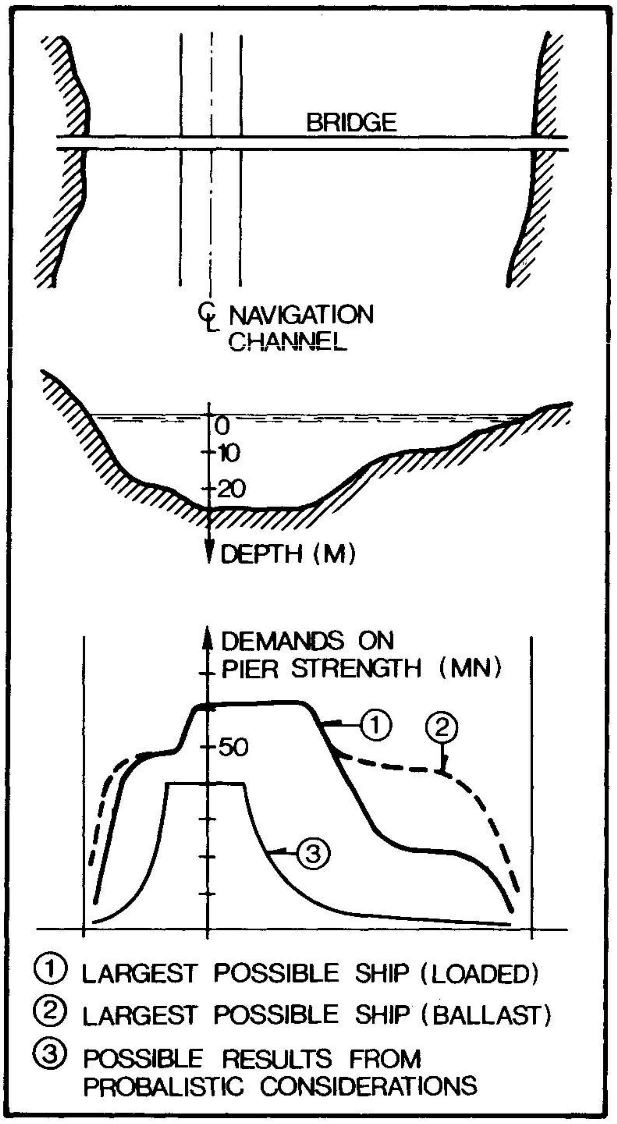


Fig 1. Ship collision forces to be taken into account when the only limiting factor is the water depth, compared with ship collision forces determined on the basis of an estimated risk. (Imaginary example).

For major bridges it is thus reasonable to treat the problem of ship collision by means of a probabilistic approach, since this allows us to weigh the risk level against the construction cost on a rational basis.

This approach requires the use of a risk assessment model. The model can be very primitive and intended only for evaluating the order of magnitude of the total risk to the bridge, or it can be more sophisticated, with a view to evaluation of individual sections or individual structural members of the bridge.

This paper describes the structure of a risk assessment model and discusses the many parameters of importance, with reference to investigations carried out in connection with major bridge projects.

2. DEVELOPMENT OF PROBABILITY MODELS FOR COLLISION ACCIDENTS

The risk assessment models hitherto employed for evaluating the risk of ship collisions with bridges have been based on the works of Y. Fujii [1] and T. Macduff [2], although the works of both authors deal with statistics for other types of accidents at sea - especially groundings and collisions between ships.

The general approach is to consider that the navigation of a ship out of control is a random process, and the probability of an accident is thus determined on the basis of pure geometry.

In connection with ship-ship collision, the general geometrical concepts are refined by means of the domain theory [3], where the "domain" is the area needed around the ship for comfortable and safe navigation. The probability of collision in a waterway is then assumed to be proportional to the number of encounters (domain infringements) taking place in the waterway.

In many respects, the transfer of experience from collisions and grounding accidents to the - comparatively speaking - very rare collisions of ships with bridges is naturally doubtful, and proper account must be taken of the ways in which bridge-passage situations differ from passage of hidden shoals and from ship encounters.

A parallel can also be drawn to another problem of current interest - that of ship collisions with offshore structures, where considerations of the risk must similarly be based on analogies to other types of accident, see for example [4].

The approach by Fujii and Macduff, and one used in the offshore field are illustrated in fig. 2.

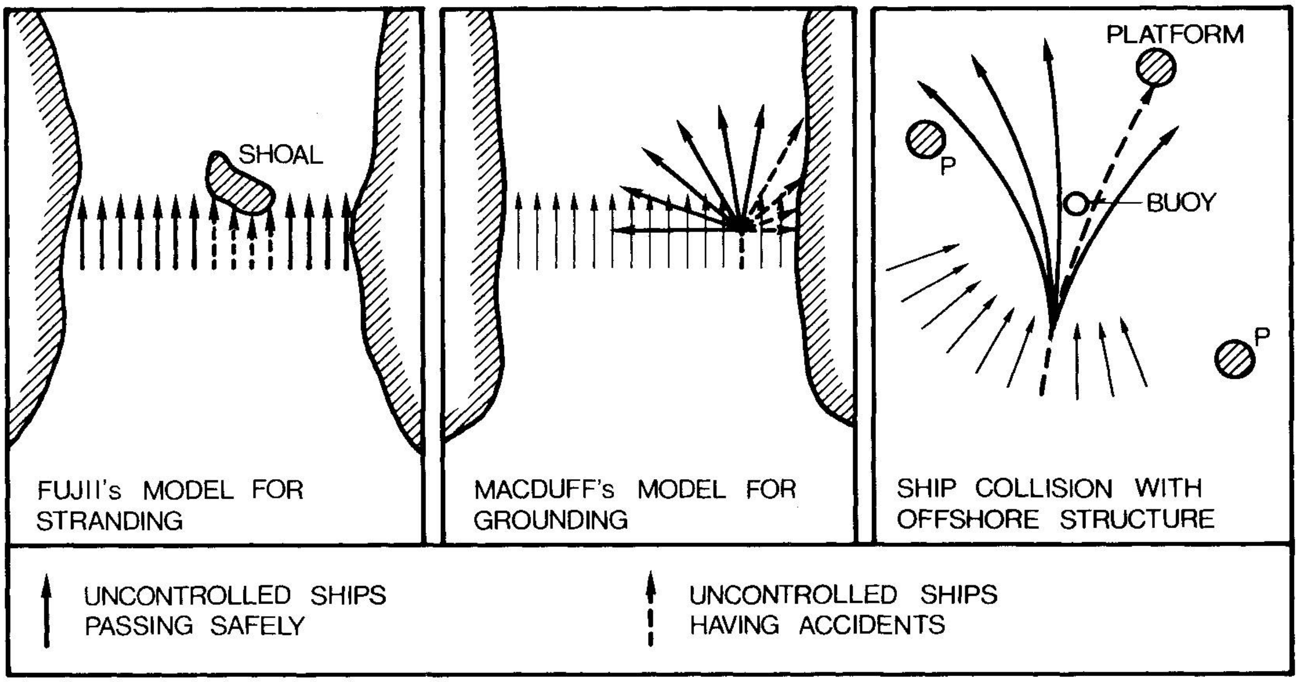


Fig. 2. Illustration of models for assessing the risk of accidents according to Fujii [1] and Macduff [2], and of collision with offshore structures [6].

2.1 The Fujii approach

Fujii et al. [1] have treated statistical data on strandings in selected Japanese waters and on collisions with drilling platforms in a waterway where a large bridge is to be constructed.

On the basis of these statistics, Fujii finds the "probability of mismanoeuvre" P in the following manner: he considers a traffic volume Q of ships , sailing in a waterway with a width W towards a rock or shoal with an effective width D+B, where B is the beam of the ship and D is the width of the obstacle shallower than the draught of the ship. The number of strandings is then approximately: $N = P \cdot Q \cdot (D+B)/W$.

When the number of strandings, the traffic volume, and the geometrical characteristics are known, P can be obtained from this equation.

For five different waters, P is found to vary between 10×10^{-4} and 0.6×10^{-4} in the case of strandings. For collision with drilling platforms, it is found that $P = 1.3 \times 10^{-4}$.

When comparing these situations with that of a bridge, it must be remembered that a bridge is a visible, permanent object which is known to shipping. The importance of this is indirectly illustrated in [1], where it is stated that for ship strandings in the Uraga Strait the "probability of mismanoeuvre" is about 2.0×10^{-4} for foreign ships, while the probability for Japanese ships is significantly smaller than 1.0×10^{-4}, because the presence of the shoal is well-known locally.

The situation of drilling rigs in the Akashi Strait is more like that of a bridge, except that drilling rigs are moved to new localities from time to time. In this situation, $P = 1.3 \times 10^{-4}$ was found.

2.2 The Macduff approach

Macduff [2] has treated statistical data on accidents in the Strait of Dover in the English Channel, considering various types of collisions and strandings.

Macduff assumes that the risk of an accident at sea P_{RG} is the product of the risk of a ship getting out of control: the "causation probability" P_C, and the probability of going aground or colliding: the "geometric probability" P_G.

The causation probability is, in principle, the same figure as Fujii's "probability of mismanoeuvre", but it is determined under other conditions and is based on a different definition of the geometrical circumstances.

Macduff calculates the geometric probability (P_G) of hitting the walls of a channel (grounding) from the equation $P_G = 4 \cdot T / \pi \cdot C$, where T is the stopping distance of the ship and C is the width of the channel. This definition of P_G is based on the concept of blind, random navigation from any point in the channel in case of loss of control.

On the basis of such considerations, Macduff finds causation probabilities for groundings of 1.4×10^{-4} and 1.6×10^{-4}.

2.3 Ship collisions with offshore structures

Various methods of estimating the probability of ship collisions with offshore structures have been reported by the National Maritime Institute in the report [4], which examines the feasibility of predicting ship-platform encounters in the North Sea by using information on shipping movements, recorded incidents, and environmental data.

Three groups of maritime traffic that might collide with an offshore installation are considered: vessels making approved visits such as tankers for loading and supply boats; vessels cruising nearby, such as fishing boats; and vessels in passage. The risk of collision for each of these groups is treated separately.

The situation of the first group of shipping is most comparable to the bridge crossing situation. For the two other groups there is the very important difference that the ships normally pass an offshore structure at a suitably big distance - and at any rate outside the safety zone (for example, 500 m) - whereas ships passing a bridge are forced to use a relatively narrow navigation span.

A great deal of research has been done into determining how tankers for loading behave when out of control, and software has been developed for computer simulation of courses after mechanical failure, cf. [5] and [6]. Theoretically, these computer models are just as applicable to the bridge-passage situation.

In connection with the planning of an offshore nuclear power plant 4 km off the coast of New Jersey, extensive probability analyses were carried out to determine the probability of a ship from the nearby shipping lanes colliding with the breakwaters of the power plant [7]. The risk assessment model used is based on probability models employed for evaluating the probability of aircraft collisions with nuclear power plants.

It is assumed that further information on methods of risk assessment for offshore structures is given in other papers of this colloquium.

2.4 Ship collision with bridges

As far as the author knows, ship collision risk assessment for bridges on the basis of detailed probability considerations was employed for the first time in connection with the Great Belt Bridge project in Denmark and, at approximately the same time, in connection with the Tasman Bridge in Australia .

The Great Belt Bridge study [8] was carried out by a Ship Collision Committee appointed by the client: Statsbroen Store Bælt. The purpose was to carry out a detailed analysis of the entire problem of ship collision with a view to the specification of collision loads.

The preliminary investigations were based on a "deterministic" approach in which each pier was designed to withstand impact forces from the biggest ships that could possibly sail in the water depth at the pier site. It was, however, realized that this simple method, clearly on the safe side, would lead to unreasonably high costs.

It was therefore decided to construct a risk model taking into account that the risk is greatest in the vicinity of the navigation channel. A number of Danish and international specialists were consulted and a model, based on a "probabilistic" approach, was constructed by the Danish consulting firm, CAP-Consult [9] . This model enabled the client to specify individual collision loads for each part of the bridge on the basis of a chosen risk level of the bridge as a whole. The client decided to chose an average period of 10,000 years between bridge interruptions due to ship collision as design basis risk level.

The Tasman Bridge study [10] and [11] was carried out for the purpose of determining the order of magnitude of the risk of further collisions with the Tasman Bridge, which was disrupted in a ship collision in 1975. Three approaches named "historical", "empirical" and "statistical" were employed:

a) Historical approach. Data on accidents, volume of traffic, climate, navigation conditions, etc. were collected for a number of bridges with a geographically similar location. On this basis, the statistical risk for the Tasman Bridge was calculated, taking account of the specific conditions relating to this bridge.

b) Empirical approach. Statistical data on accidents in the Suez Canal were translated to the conditions applying in the Derwent River, which the Tasman Bridge crosses.

c) Statistical approach. A statistical assessment was carried out on the basis of the works of Fujii and Macduff, in accordance with the same principles as are described in this paper.

The three methods all gave the same order of magnitude of the risk for the bridge, viz. 10-40 years return period of serious ship collision.

The Great Belt and Tasman Bridge studies were performed during the years 1976-79. Since then, risk assessment analyses following these principles have been carried out in connection with many bridges in Denmark and abroad designed by Danish engineers, and in connection with the New Sunshine Skyway Bridge in Florida [12]. Risk assessment analyses have probably also been employed on other bridges with which the author is not acquainted.

3. CAUSES OF COLLISION ACCIDENTS

To construct a risk model, it is essential to possess a thorough knowledge of the types of errors or failures that cause accidents to ships and, therefore, a short introduction to this subject is given below.

Many studies covering specific types of accident and/or specific geographical areas have been carried out. They are usually not directly applicable to the situation one wishes to examine, but contain a lot of useful information.

Important recent works include:
- the investigations by R.B. Dayton of 811 river towboat collisions with bridges in the USA [13],
- the study by B. Paramore et al. of the human and physical factors affecting causalities [14],
- the oil spill risk assessment by W.E. Faragher et al , in connection with the Louisiana Offshore Oil Port [15],
- the study of circumstances of sea collision by A.N. Cockcroft [16],
- many studies covering specific areas and types of ship have been published by authors from the international ship classification agencies and insurance companies.

It becomes apparent from these and other studies that the factors affecting causalities are innumerable and furthermore, that several factors generally combine to produce the accident.

Generally speaking, the factors are usually classified as follows:
- human errors,
- mechanical failures, and
- adverse environmental conditions.

Examples of causes of accidents from these categories are:

Human errors:
- inattentiveness on board the ship,
- lack of reactivity (inebriation, tiredness),
- misunderstanding between captain/pilot/helmsman,
- incorrect reading of instruments,
- incorrect interpretation of chart or notice to mariners,
- violation of rules of the road at sea,
- incorrect evaluation of current and wind conditions, etc.

Mechanical failures:
- mechanical failure of engine,
- mechanical or electrical failure of steering,
- other failures due to poor equipment, etc.

Adverse environmental conditions:
- poor visibility (fog, rainstorm),
- high density of ship traffic,
- strong current or wave action,
- wind squalls,
- poor navigation conditions owing to poor leads or awkward alignment of navigation channel, etc.

Most of the statistics reveal that human errors and adverse environmental conditions (including poor visibility) carry considerable weight, whilst mechanical failures are of minor importance.

In given waters, the distribution between the different types of error and the total frequency of accidents naturally depends decisively on the local circumstances.

The statistics also show that the different types and sizes of ships are subjected to diverging levels of risk.

4. CHARACTERISTICS OF PASSING SHIPS

It is naturally necessary to have precise knowledge of the ships passing the bridge. Data of particular importance are: type, size, speed and loading status.

Furthermore, the development of shipping in the aspects mentioned, have to be forecasted to, say, the middle of the anticipated lifetime span of the bridge. The general development tendencies in ship-building must be considered; see for example the fleet forecast made by the US Maritime Administration. Also, factors that may influence the situation locally must be taken into account: for example, deepening the navigation channel which is a possibility in the case of Great Belt [8] , or major changes in the traffic pattern which, for example, will be experienced in the Strait of Gibraltar after increasing the capacity of the Suez Canal [17] .

Having established the volume and distribution of the shipping to be taken into account, the characteristics of importance which

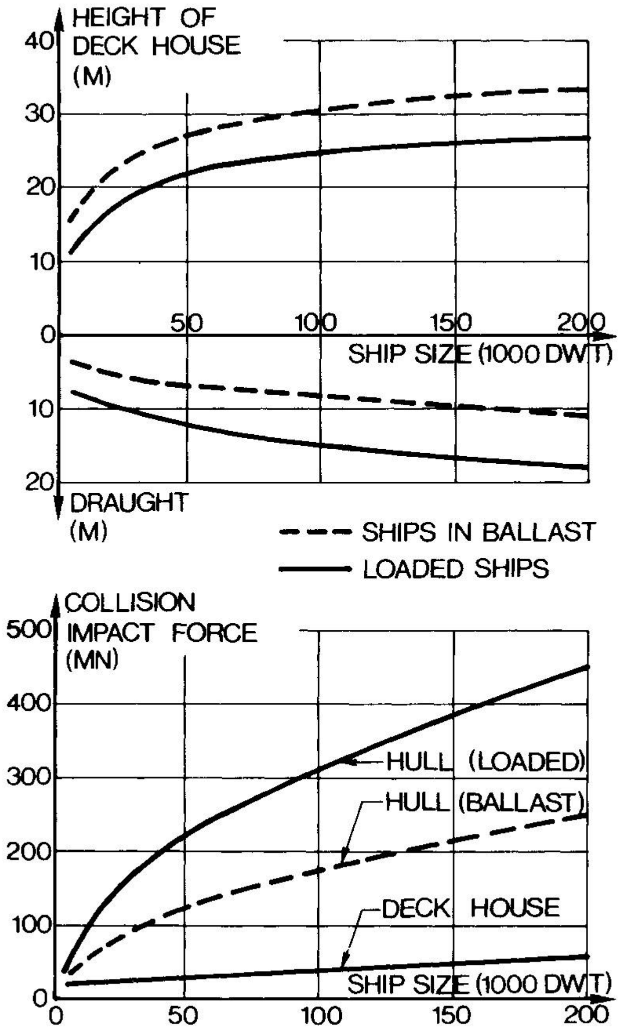


Fig. 3. Typical height, draught and collision impact forces of tankers.

are draught, height, collision impact capacity and manoeuvring qualities must be found for each type of ship.

Data on draughts are given in many journals, for example [18], and in ship registers. Data on heights of deck housing, masts and funnels are more difficult to find; measurements may be taken from ship drawings. Ship collision impact forces can be found in [8] for big ships. For small ships no material seems to have been published. Even less is known about the impact forces due to collision between a ship's deck housing and a bridge superstructure.

The types of data mentioned are illustrated in fig. 3 in which typical values for tankers are shown as the function of the size of ship.

The curves shown are only intended to illustrate orders of magnitude and tendencies; in practice, there can be considerable deviations which should be taken into account.

As suggested in the figure, it is advisable to consider ships in ballast separately because their characteristics deviate significantly from loaded ships.

Beside the geometrical and structural characteristics of the ships, their manoeuvring qualities in case of an emergency are of importance. Of particular importance are the stopping length and turning ability, which depend considerable on the size of ship. For example, an emergency stop from full ahead by applying the engine full astern is normally assumed to be proportional to the length of the ship (20 L), giving, say, 3 km for a 20,000 DWT ship and 6 km for a 200,000 DWT ship. A ship will stop faster by turning, if this is possible, see fig. 4. There is a wealth of literature on this, see for example [19] and [20].

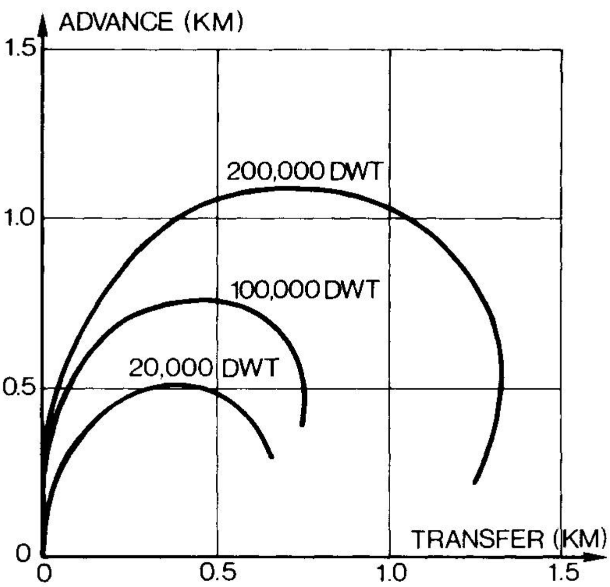


Fig. 4. Example of turning track dimensions for various tanker sizes (initial speed : 16 knots).

5. GENERAL PROBABILITY MODEL FOR SHIP COLLISION WITH BRIDGES

Based on knowledge of shipping and accident causes in general, a probability model may be formulated.

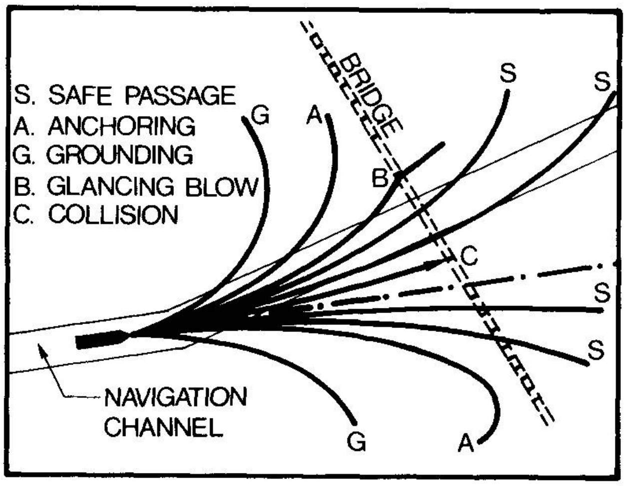
The basic concept is as follows:

Consider a bridge crossing a shipping lane.

Most ships in the shipping lane sail without problems, but a small fraction experience difficulties which cause them to lose control while passing the bridge.

Some of these uncontrolled vessels will pass the bridge safely, and others will stop or go aground, but a tiny fraction will hit one of the piers or the superstructure of the bridge, depending on the location of the piers and the vertical clearance.

Fig. 5 illustrated possible tracks of a ship out of control. Whether the bridge will be seriously damaged or not depends on the way the ship hits the bridge, the strength of the structural member in question, and the size and speed of the ship.



<u>Fig. 5.</u> Possible tracks of a ship out of control.

With this concept, the probability of failure P_{ij} of a structural member (j) of the bridge due to collision by a passing ship (i) can be expressed as:

$$P_{ij} = A_i \times G_{ij}$$

where,

A_i is the probability of the ship getting out of control, designated the <u>causation probability</u>. In principle, this probability is identical with the above-mentioned probabilities of "causation" (Macduff) and "mismanoeuvre" (Fujii).

G_{ij} is the probability of the uncontrolled ship striking the structural member in question in a disastrous way, designated the <u>geometric probability</u>. This probability is determined with regard to the strength of the member, on the basis of the geometrical constraints and on assumptions regarding how the ship moves when it is out of control.

Since, in general, all P_{ij} are negligible compared to unity and since A_i and G_{ij} are both dependent on the characteristics of the various ships, the probability of failure of the structural member j due to the passage of N ships (during one year) can be expressed as:

$$P_j = \sum_{i=1}^{N} A_i \times G_{ij}$$

Furthermore, if all P_j are also negligible compared to unity, the total probability of failure P of the bridge, taken as a whole, will be the sum of the probabilities of failure of the M individual structural members:

$$P = \sum_{j=1}^{M} \sum_{i=1}^{N} A_i \times G_{ij}$$

Analyses dealing with every single ship and its individual characteristics and reactions are, of course, not reasonable in practice. Therefore, and also on account of our ignorance of the shipping of the future, the most rational approach is to consider a suitable number of groups of ships, for example 2-3 type categories, 2-3 fault reaction categories and 5-10 size categories.

The following sections contain a discussion of the various factors that must be considered in order to arrive at the sub-probabilities A_i and G_{ij}.

5.1 The causation probability

As mentioned, this probability is assumed to be governing for all types of accidents in a given waterway which means that only the geometrical circumstances determine what kind of accident, if any, will happen in the case of error or failure. Following this assumption, it is possible to take advantage of statistics treating other more common types of accident.

The causation probability is, on the other hand, assumed to depend decisively on the local navigation conditions (climate, navigation leads and regulations etc.), and should be based on detailed knowledge thereof. Such information can be obtained in the following ways:

- Analysis of the traffic pattern in the waters in question by means of counts, radar filming, etc.
- Interviews with local, experienced pilots, masters and coast guards.
- Study of pilot´s performance on a ship simulator set for the area of the bridge crossing.

The following two methods of assessing the causation probability in a given waterway can be employed (separately or combined):

- Comparison of the local navigational conditions with those in waters where the causation probability is known better and estimation of the influence of the points of diversity.
- Evaluation on the basis of statistics of all types of accidents in the waterway in question.

Where it is found warrantable to differentiate between different types of ships, the best approach will be first to estimate the average causation probability and then to estimate deviations for the individual types of ship in such a way as to keep the average.

Table 1 lists causation probabilities as calculated or estimated in different situations. The figures given are averages for all types and sizes of ships in the localities in question.

The statistics for the Thames Estuary buoy is included for the sake of comparison. Buoys are at particular risk because they are used to steer by and the consequences of a collision are not such as to inspire fear.

Before leaving the causation probability the most important uncertainties should be mentioned. Firstly, the basic assumption of independence of the geometrical circumstances needs statistical support, which is not available for the time being. Secondly, the effect of variations in navigational conditions (current, visibility, regulations, etc.) have to be judged as well, almost without statistical support.

In two cases, [11] and [12], it has been attempted to reduce these and other uncertainties by comparing model calculation results with statistics of actual collision accidents.

Locality	Type of accident	Source	Type of data	Causation probability
Dover Strait	Grounding	[2]	Statistics 31 accidents	1.4 to 1.6
Japanese Straits	Stranding	[1]	Statistics 50 accidents	0.7 to 6.7
Japanese Straits	Drill. Pl. Collision	[1]	Statistics 16 accidents	1.3
Thames Estuary	Buoy Collision	[4]	Statistics 7 accidents	80
Worldwide	Bridge Collision	[10]	Statistics 10 accidents	0.5
Tasman Bridge	Collision	[10] [11]	Estimate	0.6 to 1.0
Great Belt Bridge	Collision	[9]	Estimate	0.4

Table 1 Causation probabilities for different water and different types of accidents.

5.2 The geometric probability

The position of a ship when control fails and the course and speed of the ship afterwards determine if and when the ship will strike the bridge.

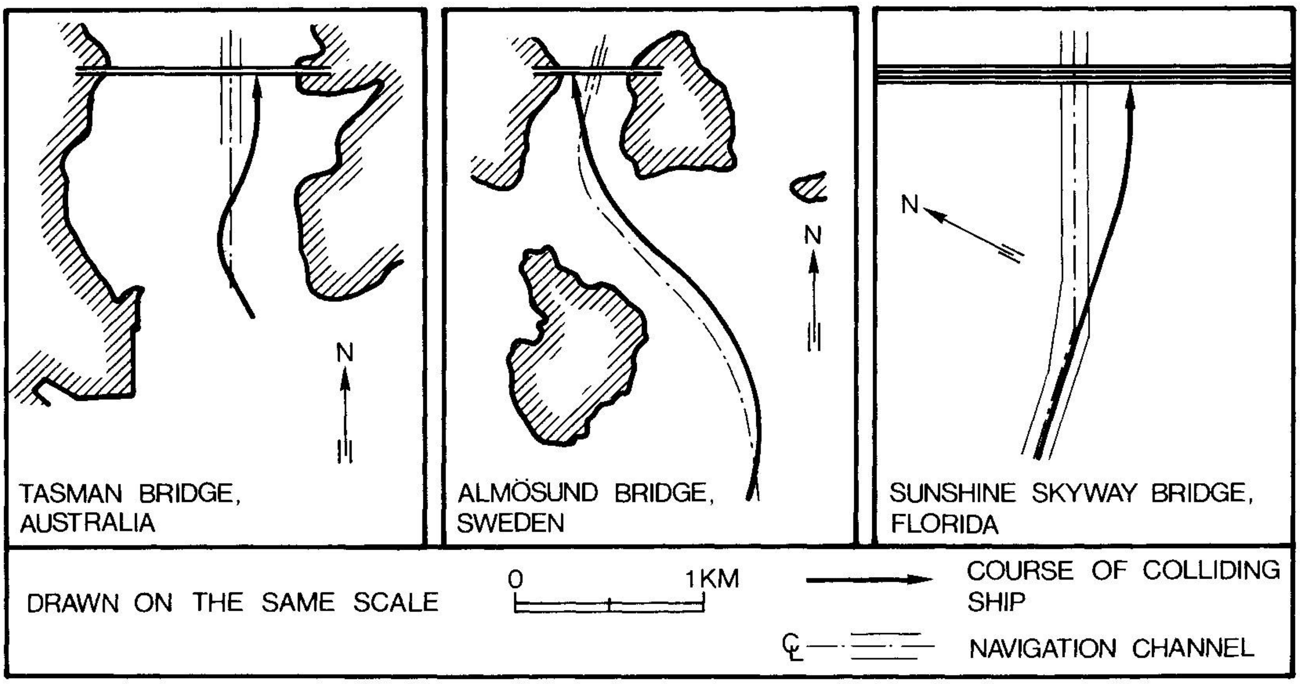


Fig. 6. Course of ships involved in three major bridge collision accidents.

To illustrate actual movements of uncontrolled ships, fig. 6 shows the tracks of the vessels involved in three of the worst bridge collision accidents experienced.

Fujii [1] assumes that the ships are uniformly distributed over the whole width of the waterway and thus calculates the geometric probability for a bridge pier as simply the width of the pier (plus beam of the ship), divided by the total width of the waterway.

In Macduff's studies [3], it is assumed that the ship can travel in any direction within a 180° arc and that it will move no further than its stopping distance from the point of failure. He does not suggest a method for calculating the geometric risk for fixed objects in the navigation channel, but from the general concept that loss of control sets in randomly at any point in the channel, it follows that the geometric probability can be calculated as done by Fujii.

The assumption that the ship traffic is distributed over the entire width of the waterway implies the same risk over the entire bridge line. However, this is generally an unrealistic assumption, because the traffic will usually be concentrated in a navigation channel leading through a navigation span, and it is obvious that the geometric probability will then be greatest in the immediate vicinity of the navigation channel and will diminish rapidly towards land.

It is shown in [10] and [11] how Macduff's approach might be employed in this situation.

The general approach proposed here is to assume that the failure of control sets in at a random location in the navigation channel. From this position, the ship moves forward in a direction and on a course depending on the characteristics of the ship, the weather and the sea, the type of failure and the counteracting actions of the crew. The probability of the ship now striking a structural member of the bridge (pier or superstructure) in a destructive way is then assumed to be the geometric probability G.

It is convenient to split up G into two factors, G^h and G^v, where G^h takes into account the horizontal geometry and G^v reflects the vertical and structural constraints.

5.2.1 G^h

G^h is the probability that the uncontrolled ship takes up a collision course.

All courses crossing the bridge line within collision zones, as shown in Fig. 7, are considered to be collision courses.

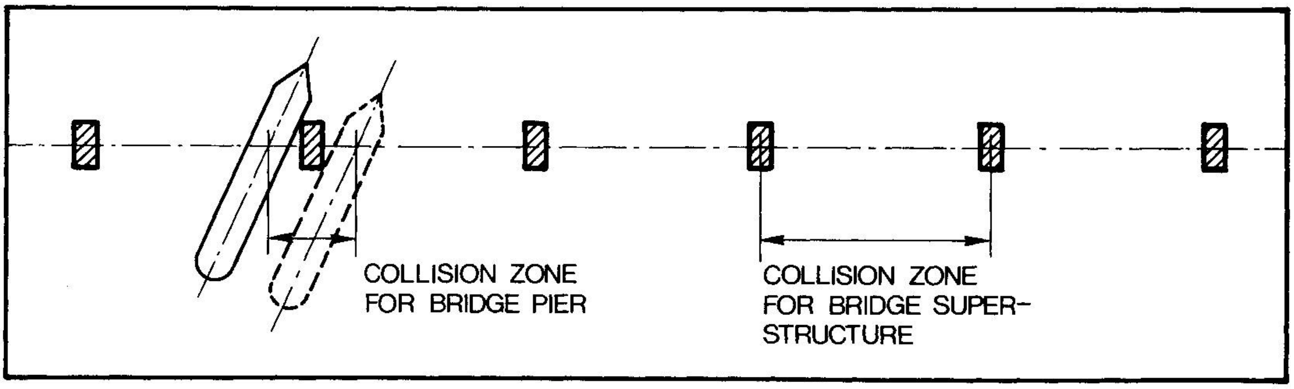
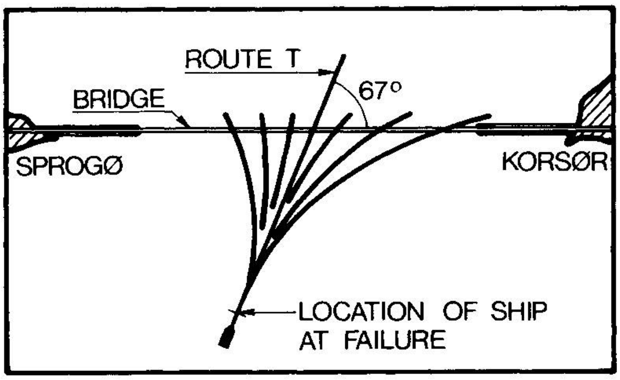


Fig. 7. Collision zones.

Ideally, this probability should be determined by predicting the ship movements in all conceivable failure and error situations and weighing the results by the relative probabilities of occurrence of these situations. Even if rough information on the distribution of error causes exist, refer section 3, and the corresponding possible movements of the ship are known, refer section 4, the general lack of information in this area implicate that simplified assumptions must be made.



In the Great Belt Bridge project [8] and [9], a distribution of courses of ships out of control, as shown in fig. 8, was assumed. All courses within a chosen curvature range were regarded as equally frequent. The idea was to represent, in a simple way, an average of possible movements of the most important part of the local shipping.

Fig. 8. Estimate of possible courses of ships out of control towards the Great Belt Bridge (from [8] and [9]).

In the risk assessment for the Sunshine Skyway Bridge [12], a more differentiated model has been employed, in which the courses of the ships out of control were not assumed to be uniformly distributed within a fan but were assumed to be concentrated partly in the middle of the fan and partly near the limiting curves of the fan, reflecting different failure or error causes. Furthermore, in this risk assessment, the probability of an accident occurring was not regarded as equally great over the entire length of the channel, but to be greater at bends in the channel.

5.2.2 GV

Many of the ships which, from the analysis of ship movements in the horizontal plane, have a possibility of damaging the bridge, will not actually do so. There are a number of limiting factors:

- ships with a greater draught than the water depth at the bridge-line will not reach the bridge,
- ships with a lower height than the clearance will not strike the bridge superstructure,
- ships with a smaller impact energy than the capacity of the structural member in question will not destroy this. The impact energy will be small in the following cases: eccentric forms of impact; low speed of ship at moment of impact; and small size of ship.

In practice, the limiting factors can be dealt with by defining individual probabilities GV for the individual piers and superstructure spans.

The principle is shown in fig. 9 for a typical pier and a typical span of a bridge superstructure. The curves have been constructed on the basis of the general data in fig. 3 and the local water depth and clearance.

The course of these curves can be divided into 3 sections, reflecting three intervals of ship sizes:

1. ships that are too small to damage the bridge;
2. ships that are tall enough or strong enough to damage the bridge; the probability of destruction increases with increasing size of ship;
3. ships with too big a draught to reach the bridge-line.

The effect of establishing underwater embankments to protect the bridge can be evaluated by defining G^v in accordance with the reduced water depth, i.e. by transferring ships from category 3 to category 2.

The factor of probability defined for category 2 ships is to take into account that not all collisions are equally dangerous.

This factor should be substantially smaller than 1.0 for bridge piers as most impacts will be "glancing blows" or impacts with reduced speed.

Some indication of the factor may be derived from the distribution of ship speeds and crossing angles when passing the bridge line which can be found in the model calculation G^h mentioned above. Another approach is to evaluate the factor on the basis of statistics on extent of damage experienced in ship-ship collisions [21]. Values between 0.05 and 0.30 have been used in ship collision risk assessments, [9] and [12].

For bridge superstructures it is more likely that a collision leads to destruction and consequently factors in the magnitude of 0.7 to 1.0 seem reasonable.

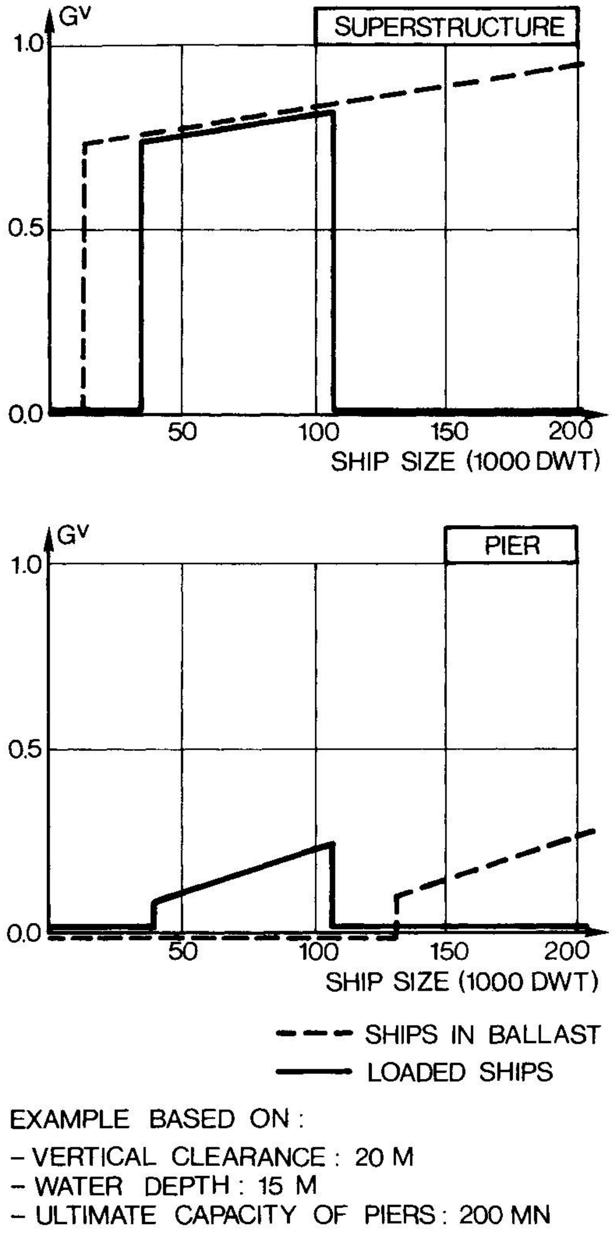


Fig. 9. Probability of destructive collision with a bridge pier or a bridge superstructure, as a function of the size of ship. (Imaginary example).

5.3 Summary of model calculations

Following the method outlined in the chapters above the steps in a ship collision risk analysis will be:

1) Acquire detailed information on the ship traffic; break down the volume of traffic into suitable categories as regards both size, type and behaviour in error and failure situations and deal with each separately.

2) Estimate the causation probability for the waterway as a whole and for each group of ships.

3) Calculate the two constituents, G^v and G^h, of the geometric probability for each structural member of the bridge and each group of ships.

4) Calculate the total risk for each member by summation for all groups of ships.

5) Calculate the total risk for the bridge by summing the risk for all the members.

6. FINAL REMARKS

The paper gives a background to ship collision risk model design for bridges and discusses the parameters taken into account at the present modelling stage.

The author has found very few examples published on collision risk assessments for bridges. He is convinced that many studies have been carried out and appeals to people who have been involved in such risk assessments to offer a contribution to this colloquium.

In particular, it would be desirable to learn about cases where more advanced models, than those reviewed in this paper, have been considered. For example, it seems very likely that simulation studies known from the offshore field have already been utilized in the bridge field.

For the time being, the accuracy of a detailed numerical assessment of the risk is doubtful owing to the shortage of basic data and - naturally - owing to the lack of knowledge regarding the shipping of the future.

The value of a risk analysis lies, therefore, in the view of the author, mainly in the fact that it enables us to weigh up the risks to the bridge in a systematic manner, with a view to achieving an overall rational design.

The model considerations are particularly suitable for comparing alternative bridge solutions. The author's experience indicates that such an analysis will often have a decisive influence on the main design of the bridge, for example with regard to length of spans, height of superstructure and strength of piers.

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