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Theme C

Evaluation of Collision Probabilities
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Evaluation of Collision Probabilities for Offshore Structures

Evaluation des probabilitiés de collision pour les constructions offshore

Beurteilung der Wahrscheinlichkeit von Kollisionen bei Offshore-Bauten

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Michael Barratt was born in 1934, and gained M.Sc. and B.Sc. (eng.) degree from the University of Southampton. He worked for several years on the development of Hovercraft before joining the National Maritime Institute. His recent work has been concerned with marine traffic collision risks, and ship manoeuvring simulation.

SUMMARY
Offshore structures, such as oil production platforms, are vulnerable to collisions with a variety of vessels, but the most serious consequences are to be expected from passing ships, unconnected with the operation of the structure. This paper introduces some of the methods which have been used to estimate the risk of collisions, and considers the limitations inherent in such estimates.

RÉSUMÉ
Les constructions offshore, comme les plates-formes d'exploitation pétrolière, courent le risque de collision avec toutes sortes de vaisseaux mais l'on peut s'attendre à ce que ce soit les navires de passage, qui n'ont rien à voir avec l'exploitation de la construction, qui entraînent les conséquences les plus graves. L'article présente certaines méthodes adoptées pour évaluer le risque de collision et considère les limitations inhérentes à de telles estimations.

ZUSAMMENFASSUNG
Offshore-Bauten, wie z.B. Oelproduktionsplattformen, sind der Gefahr von Kollisionen mit den verschiedensten Schiffen ausgesetzt, wobei die schwersten Folgen durch Zusammenstöße mit vorbeifahrenden Schiffen, die mit dem Betrieb der Konstruktion nichts zu tun haben, zu erwarten sind. In diesem Referat werden einige der Methoden, die zum Zwecke einer Einschätzung des Kollisionsrisikos herangezogen worden sind, aufgeführt und die Grenzen besprochen, die einer derartigen Einschätzung naturgemäß gesetzt sind.

1. INTRODUCTION

Offshore structures, mainly in the form of oil and gas drilling rigs and production platforms, have become increasingly common in Northern European waters in recent years, and efforts have been made to estimate the likelihood of ships colliding with them. This paper introduces some of the methods which have been used for collision risk estimation, and assesses their value and limitations.

It is necessary to consider separate categories of collision, for vessels visiting the structures or in attendance, and the original traffic in the area, particularly passing vessels. Of these risks, the latter is potentially more important because of the larger sizes of vessel which could be involved.

It is possible to compare the risk for a proposed structure with the risks for existing structures, taking into account traffic densities and environmental factors such as visibility. However, estimates of the absolute likelihood of collision by passing vessels at present depend upon analogies with other marine collisions, and some methods which have been used are discussed.

Simulation methods are considered to be particularly applicable to specific cases involving visiting vessels, but require further information to provide more reliable probablistic inputs for general use.

The sources of data and the methods mentioned are not claimed to be exhaustive, but rather to provide an introduction to the possibilities and limitations of collision probability evaluation for offshore structures.

2. TYPES OF INSTALLATION

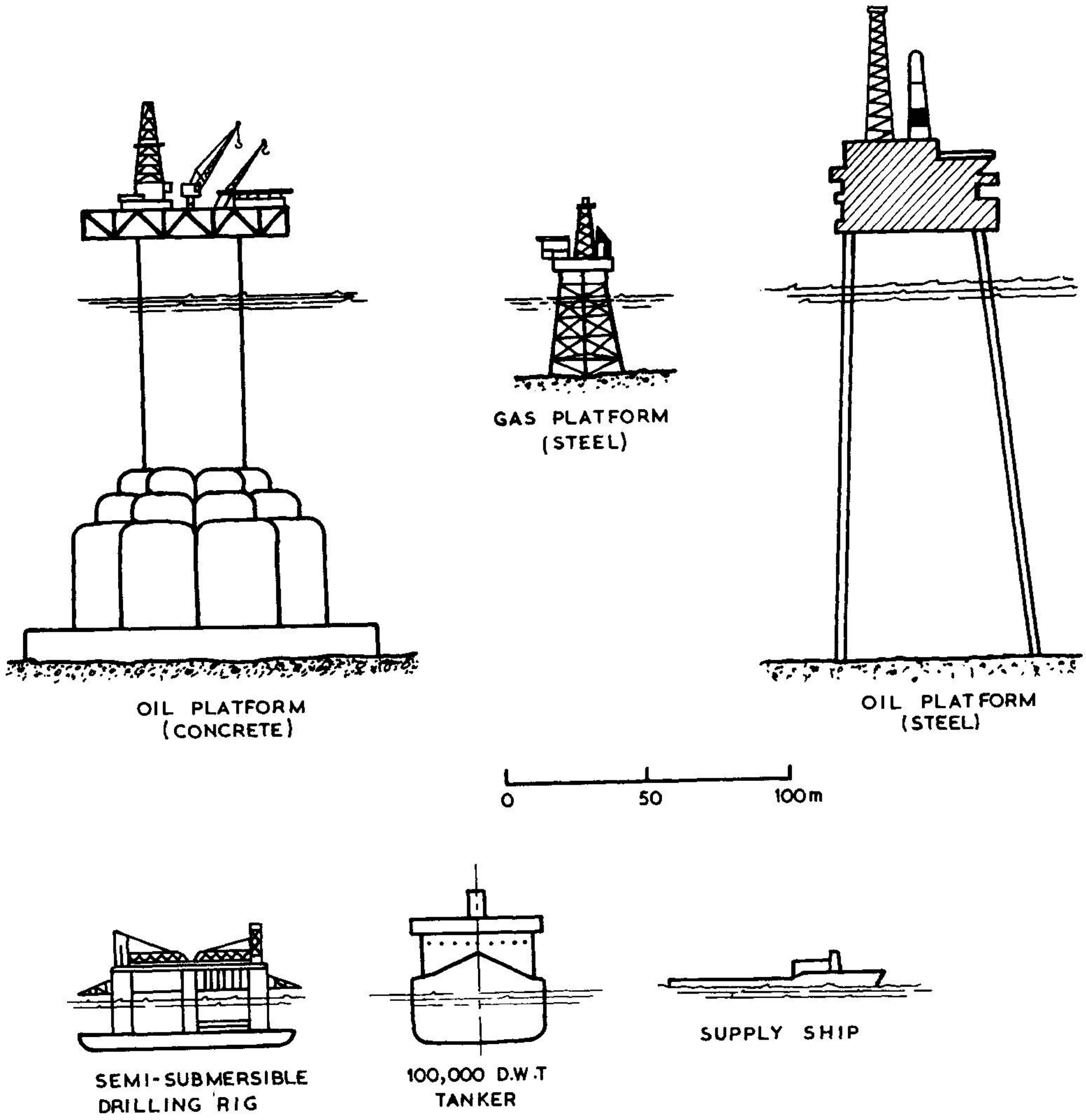
The commonest type of offshore structure for which risk estimates are required is the oil or gas rig or production platform. These can cover a wide range of types and sizes. Rigs for performing exploratory drilling are moveable from place to place, and in sufficiently shallow waters take the form of jack-up structures, supported by legs on the sea bed. In deeper waters semi-submersibles are used, moored to the sea-bed. In the deepest waters drill ships are used, with dynamic positioning devices to maintain station above the drill.

Fixed production platforms may well remain in position for many years and therefore become permanent features posing a possible collision risk over an extended period of time. They consist of two types, steel structures attached to the sea-bed by means of piles, and reinforced concrete structures which remain in place because of their weight.

A range of types of offshore structures and attendant vessels is shown in fig.1.

3. VESSELS INVOLVED IN COLLISIONS

Different types of shipping can be involved in collisions with offshore structures, and a basic breakdown of these is shown in the table of collision risk categories. A fundamental distinction must be drawn between collisions involving the original traffic present in the area and that associated with the structure. This division is not



TYPICAL STRUCTURES AND ATTENDANT VESSELS

FIG. 1

straightforward to make, as will shortly be shown, but is necessary because of the different importance attached to risks external and internal to the operation.

This paper will deal mainly with collisions with the original passing traffic, as estimates of this risk are needed when considering operations in a particular area. The other categories are likely to depend strongly on operational procedures.

COLLISION RISK CATEGORIES

ORIGINAL TRAFFIC		ASSOCIATED VESSELS	
ON PASSAGE	FISHING etc	VISITING	STANDING OFF

3.1 Original Traffic

The original traffic in the area is the shipping measured or to be expected in the absence of the structure. It consists of vessels undertaking voyages between ports, generally on pre-determined routes, and others such as fishing vessels, whose pattern of movement will depend upon day-to-day considerations. Military and pleasure vessels may also be included in this category.

3.1.1 On Passage

The vessels on routes between ports are of major importance because they are likely to be the larger vessels in the original traffic, and therefore could inflict the greatest damage on any structure with which they collided. Fortunately, their routes follow regular patterns, and the traffic density due to this source can be estimated.

3.1.2 Fishing etc

A large proportion of the vessels approaching within the safety zones of production platforms consists of trawlers and other fishing vessels, and these are therefore a potential source of accidents , although they are comparatively small in size. There are two difficulties in analysing this class of traffic, firstly that the original pattern can often not be described in statistical terms, and secondly that the pattern may be greatly modified by the presence of the structures.

The numbers and distribution of fish in many areas vary not only in a cyclical way from season to season, but also in ways that are largely unpredictable from year to year. Also there is reason to believe that fish are attracted to structures, thus making the adjacent sea a potentially profitable fishing ground.

The activities of military and pleasure craft are also essentially unpredictable.

3.2 Associated Vessels

The vessels associated with the structures can conveniently be divided into those which need to approach close to the structure, for supply or other purposes, and those which will normally stand off, e.g. in the role of safety vessel or a tanker loading oil from a buoy at a distance from a production platform. With the exception of the tanker, such vessels are comparatively small and unlikely to cause disastrous damage.

3.2.1 Visiting

Supply vessels are required to unload a wide variety of stores and equipment, sometimes in severe weather conditions. It is occasionally necessary to lift large loads by crane from a vessel experiencing considerable motions. Minor collisions are an inevitable hazard.

3.2.2 Standing off

These include the safety vessel which will normally be in attendance to an oil production platform, and in some cases tankers loading oil from a buoy or other mooring. In this case we have to consider the possibility of mechanical failure, followed by the vessel drifting on to the platform. The consequences of such a collision by a tanker could be severe, but the attendant safety vessel would be available to give towing aid.

4. DATA SOURCES

Before considering methods of risk estimation in detail, the sources of data which are available or could be obtained need to be known. It must be emphasised that certain types of information involving human behaviour are either unreliable or simply not available.

As a general point, all the data sources are necessarily historical in nature, and predictions of future risks must take this into account.

4.1 Collisions

Apart from collisions with fixed structures, data on other collisions can be valuable in supporting risk estimates on the basis of analogies between the different types of collision.

4.1.1 Fixed Installations

Data on collisions are collected by oil companies and by national governmental departments. Clearly information on actual occurrences is of vital importance, but it is limited in extent (ref.1). In particular, collisions by passing vessels in the North Sea are sufficiently rare to prevent any sort of statistical analysis. However, information on incidents involving support vessels does provide valuable operational guidance for operators.

4.1.2 Light Vessels

Because of the shortage of data from structures, collisions with fixed light vessels have been considered as a possible guide. Although the number of collisions of this type is still not large, information supplied by Trinity House and other authorities gives useful guidance on collision rates with fixed vessels.

4.1.3 Other Vessels

As a final source, collisions between moving vessels have been used, although this may be straining the analogy rather far. Nevertheless, such information is available in sufficiently large quantities for a correlation to be possible between the traffic density and the number of collisions (ref.2)

4.2 Infringements

Production platforms are surrounded by a designated safety zone of 500m. radius, which is out of bounds for vessels not having business there. Details of contraventions of these zones go to national authorities, and such information is a guide to possible 'near misses' (ref.1). However, over a period of 5 years in the British sector of the North Sea, three quarters of these contraventions have been by fishing vessels, presumably drawn by concentrations of fish, rather than by ships simply passing through the area.

4.3 Traffic

The traffic density and pattern in the areas under investigation is a major factor influencing the collision risk. Depending upon the area, information may be available or obtainable by a variety of methods which will now be considered.

4.3.1 Surveys

In a few cases, particularly for busy traffic regions, marine traffic surveys have been performed, using extensive resources and including individual identification of vessels, (eg ref.3). For most areas of interest however, such information will not be available, nor would the cost be easy to justify. Existing surveys have been valuable in checking and calibrating the alternative, less comprehensive methods of obtaining traffic data (ref.2).

4.3.2 Aerial Observations

Aerial surveys are a quick way of obtaining the shipping distribution over a large region, (ref.3), although many flights are needed to establish the shipping density distribution accurately. Further information may be necessary to obtain speeds and courses, and the sizes and types of vessels.

4.3.3 Voyage Details

Details of vessels entering and leaving ports are obtainable from Lloyd's List and harbour authorities. Provided that the vessels can be assumed to take a direct course between ports, and all possible combinations of ports have been considered, this is an economical way of building up the regular traffic pattern. Further assumptions are, however, needed on such details as the spreading of courses within a particular route.

4.3.4 Voluntary Observer Ships

Some 10% of the world's merchant ships send back weather observations to meteorological organisations. The geographical distribution of such reports is thus a guide to the general distribution of ships. Subject to an under representation of small vessels, these ships appear to be a reasonably representative sample of the world fleet, but caution is needed, as reports are not necessarily sent back at uniform intervals. However, traffic distributions can be obtained over wide areas, and with suitable calibration form a valuable alternative source of data (ref.2).

4.3.5 Fishing Vessels

As was mentioned earlier, fishing vessel distributions in many areas are unpredictable from year to year, and appear to be influenced by the presence of fixed structures. However, national authorities do record activity within different regions, and a qualitative impression may be gained of the regions which have had most fishing vessels in recent years.

4.4 Environment

The importance of the different environmental factors depends upon the type of collision which is being considered. For collisions involving passing vessels, failure to sight or identify a structure sufficiently early could be a contributory factor, and therefore the visibility is of major importance. For visiting vessels close in attendance to a structure, the sea state will be the main consideration. Strong tides could affect the time available after mechanical failure, or possibly lead to misjudgement of closest points of approach.

4.4.1 Visibility

The variation of visibility has been shown to be important in collisions between ships (ref.4), and the same may be inferred to be true for ships and fixed structures. Observations of visibility are widely available through meteorological organisations, and the distribution of reduced visibility may be found over extended areas.

4.4.2 Sea State

Sea state observations at sea have been published, eg (ref.5), for large parts of the earth's surface. Larger numbers of observations are of course available for the regions with most traffic, where collisions would be the greatest hazard. Tidal streams are available on charts for navigational purposes.

4.5 Failure Rates

Estimation of failure rates of various types is implicit in risk estimates based on analysing the possible causes of collisions. It is in this area that the available data is weakest.

4.5.1 Mechanical

Information on mechanical breakdowns is available for instance from Lloyd's intelligence, and will give considerable statistical help. However, close examination shows that most such breakdowns occur at convenient anchorages, indicating the ability to continue far enough to reach relative safety, or avoid a fixed structure.

4.5.2 Human

The frequency of human errors is the most difficult of all to estimate. Not only will such errors be complex functions of many variables, but reliable information on them is extremely hard to obtain.

Examination of individual ship collisions has shown that it is often possible to determine the situation preceding the collision (ref.6), but admissions of errors are unlikely to be available.

5. RISK ESTIMATION

From the general consideration of types of collision, it will be seen that collisions involving passing traffic merit the greatest attention, both because of the greater damage to be expected, and because they are accidents involving vessels unconnected with the business of the structure. However,it will also have been noted that not many data are available on such collisions because of their infrequency, and that contributary failure rates are difficult to estimate reliably.

In considering possible methods we shall therefore pass from the comparatively crude but reasonably reliable, to methods seeking more detailed answers but requiring more assumptions about the causes of collisions.

5.1 Relative Risks

Probably the most reliable estimate possible at present is the overall comparative risk of collision for positioning a structure at alternative locations. This can be based on the traffic density and the visibility at the positions compared.

The basic assumption is that the overall collision rate is proportional to the flow density - the number of vessels passing within unit distance in unit time. This is linked with the concept of encounter radius originally developed for air traffic control theory (ref.7) and now used in ship-ship collisions, where the number of collisions is assumed proportional to the number of 'encounters'. In the absence of avoidance action, the assumption may be considered self-evident, and for practical purposes it should only break down when the density of shipping is such that one vessel might impede another.

The influence of visibility can be based on analysis of the variation of collision rates with visibility for collisions between ships. (ref.8) A 'fog collision risk index' (FCRI) has been proposed which links the collision rate to the amounts of the thickest fog. Some caution should be exercised in applying it outside the Northern European Waters for which it was derived, and also in using it for fixed structures rather than ship-ship collisions.

We then have

Collision rate = k x traffic flow rate x FCRI

and a direct comparison may be made with some chosen location.

5.2 Analogies

The use of the above method to obtain estimates of the collision frequency in absolute terms is hampered by lack of information capable of giving the size of the constant k in the above equation. As mentioned earlier, collisions by passing ships with fixed structures are too rare to allow a reasonable estimate, and so more or less distant analogies have been used.

5.2 1 Light Vessel Analogy

The light vessels stationed around the coasts of Britain and in some other European waters have suffered enough recorded collisions to allow estimates of collision rates. Also, they are situated in regions where the traffic flow can readily be estimated. In many cases they also act as weather reporting stations, and so allowances can easily be made for the visibility. Against these advantages must be set their dissimilarity in size with at least the larger fixed structures.

The effect of size is not clear when considering such analogies. On the one hand, the larger targets can be detected at a greater distance; on the other, larger course deviations are necessary to avoid them. Some idea of the balance of these effects as size becomes smaller is given by the fact that large 'high focal plane' bouys suffer much larger numbers of collisions than would be expected on the basis of the nearby traffic. It is probable that all large fixed objects attract some traffic for navigational purposes, whether that is one of their purposes or not.

Bearing in mind all such limitations, the light-vessel analogy has allowed estimates of collision risk which have the major virtue of requiring comparatively few basic assumptions.

5.2.2 Ship-ship collisions

Ship-ship collisions are, of course, unlike collisions with fixed structures in that some at least must be ascribed to misunderstanding each others' intentions. However, it is interesting to compare the results of this analogy with the previous one. Taking the effect of a fixed structure as equivalent to an extra vessel within an area, we can calculate the incremental effect of this extra 'vessel' on the number of collisions.

It is generally assumed that the number of collisions between vessels is proportional to the number of encounters between vessels, that is the number of times the vessels approach within some arbitrary distance of one another. But the number of encounters is proportional to the square of the shipping density (eg ref.7).

Hence the collision rate

$c = k'n^2$ where n = number of vessels in given area
and $dc/dn = 2k'n = 2c/n$

That is, the number of collisions per extra vessel or structure is twice the mean number of collisions per vessel.

Given the traffic density in the area, and the collision rate for that traffic density, the expected collision rate for the extra obstruction can then be calculated. It is interesting to find (ref.2) that the result of this calculation can compare closely with that of the light vessel analogy.

5.2.3 Safety zone infringements

Although outright collisions with structures are very rare, there are more frequent infringements of the 500m. radius safety zones which surround oil production platforms. The assumption can reasonably be made that these events for passing traffic correspond to gross failures of navigation, and hence position within safety zones approaches a random distribution. Therefore, collisions = infringements x(structure+ship) size / safety zone size

Since most infringements are by fishing vessels which are presumably within the zone deliberately, it is not surprising that this method has initially led to considerably higher estimates of collision frequency than those previously mentioned. However, if allowance is made for the proportion of infringements which are not fishing vessels, the agreement is remarkably close.

5.3 Simulation

Simulation techniques can provide estimates of the frequency of collision, but at the moment this is not their greatest strength because of the lack of suitable probabilistic data, particularly on the actions taken by mariners. At present they may be more valuable in giving insights into the nature of particular types of incident. It may also be possible to devise and practice procedures for use in the event of mechanical breakdowns.

Three stages of simulations appropriate in the collision context may be identified - first the determination of a traffic pattern or route structure, then the allocation of probabilities of actions or failures, and finally the calculation of the outcomes of each event.

5.3.1 Traffic Pattern

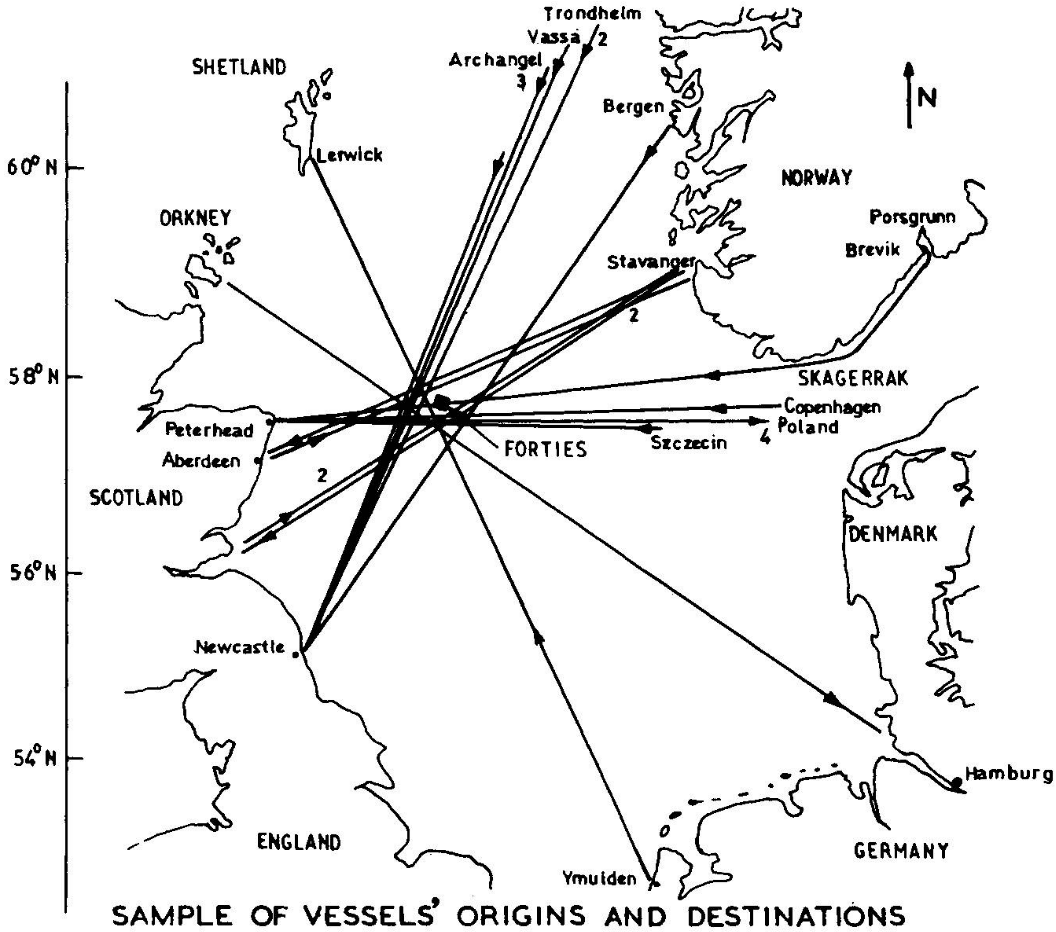
The traffic pattern can be built up in a number of ways, but it must be capable of generating sample ships' tracks. This is normally done on the basis of entry and exit points to the region under investigation, together with a spread of tracks about each route.

Thus fig.2 from ref.9 shows routes across the North Sea which pass near the Forties field, and a sample of actual tracks near the field. A more complex representation was made in ref.10 for the English Channel, taking into account the observed spreading of ships' tracks and the constraints of existing and postulated routeing schemes. Alternatively, when considering vessels with business in the region of a structure, a point on the track may be well defined, as for instance a tanker approaching a buoy.

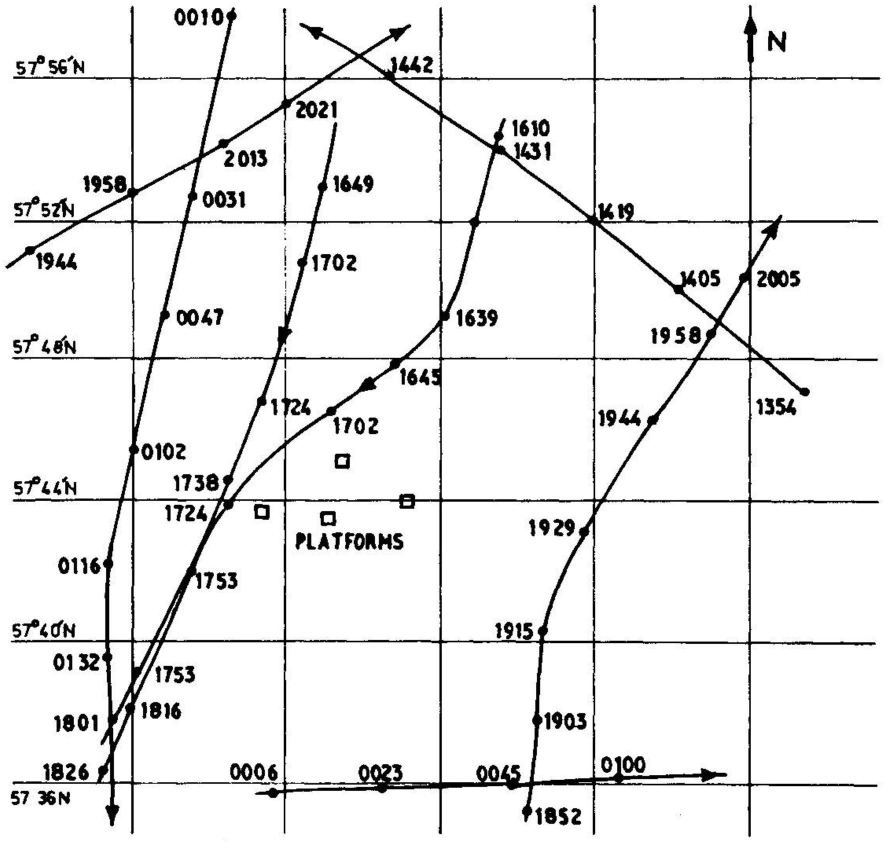
5.3.2 Actions and Failures

At some stage during the simulation, it will be necessary to generate events such as a mechanical failure which could lead to collision risk, and/or some human error or omission which could affect the outcome. For instance, for tracks passing near a structure, a mechanical failure could leave a ship out of control and liable to drift on to the structure. The probability of mechanical failure can be estimated, but it must be born in mind that recorded mechanical failures do not appear to occur as random events, as mentioned earlier. However, in the main, we are dealing with quantifiable probabilities, and sensitivity analysis is available to check the importance of the assumptions.

The probability of various types of human error is much more difficult to estimate. We have to consider the chances of mariners taking actions such as approaching a structure for navigational purposes, taking avoidance action at various stages, and making random errors in their judgements. More fundamentally difficult is to estimate the likelihood of the inexplicable events, when a vessel fails to take any avoidance action at all, apparently having failed to detect a large



SAMPLE OF VESSELS' ORIGINS AND DESTINATIONS



TYPICAL DAY'S TRACKS OF PASSING VESSELS

FIG. 2

structure. Since the events whose probability we are trying to evaluate are in any case rare, it is possible that an appreciable proportion of them defy close analysis.

5.3.3 Outcomes

The outcomes will normally be found by a Monte-Carlo approach, with the algorithm guiding each vessel through a set of decision points, subject to random responses. The model may include the dynamic response of the vessel to its controls, or to the action of wind and waves (ref.11). At the end of a large number of runs, a proportion of vessels will have experienced collisions, or a range of miss distances will have been generated. The most reliable results are likely to be obtained for closely defined situations, such as vessels approaching a loading buoy (ref.12).

5.4 Damage

The calculation of structural damage is beyond the scope of this paper, but some pertinent facts do emerge from consideration of the available data and the possible categories of collisions.

Vessel sizes and types are likely to be known fairly accurately through port arrivals and departures and such publications as Lloyd's register.

Impact velocities will fall into two categories; ships on passage which are likely to be travelling at approximately their service speed, and drifting vessels which will have attained the velocity dictated by the wind and waves.

Therefore, the severity of typical collisions should be largely determinate, as far as the larger vessels are concerned. Lesser impacts by supply vessels are of course a different question.

6. DISCUSSION

A number of ways of calculating collision probabilities for offshore structures have been considered. They have largely concentrated on passing vessels, because of the more serious consequences of this type of collision.

The relative risks of different geographical locations can be estimated with reasonable confidence. Methods based on analogies with other types of incident have been described, which give remarkably consistent values for overall collision rates. However, the absolute values obtained from them should still be treated with caution.

Simulation methods, based on the analysis of possible types of event leading to collision risks, are probably not at their best for collisions by passing vessels because the events which lead to these collisions are not well understood. Their best applications may well be to particular operational risks in the region of structures.

In general, approximate estimates of collision risks can be made which allow the evaluation of new geographical locations for offshore operations. More refined methods will allow the examination of operational and emergency procedures. This introduction to some of the possible approaches is intended to stimulate discussion and the exposition of improved methods.

7.ACKNOWLEDGEMENTS

My thanks are due to all those whose work has contributed to this paper, particularly where considerations of confidentiality have made a specific acknowledgement impractical. This paper was produced under the auspices of the National Maritime Institute, but the opinions are those of the author.

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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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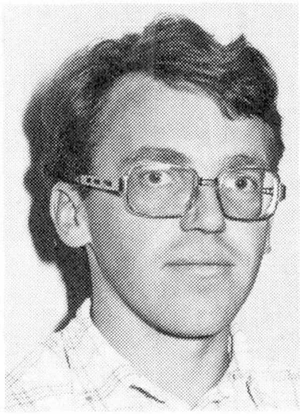


Ole Damgaard Larsen, born 1942, graduated from the Technical University of Denmark as a civil engineer in 1965. His professional work has mainly been within the fields of bridges and structural engineering. He has been involved in ship collision studies in connection with several bridges in Denmark and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

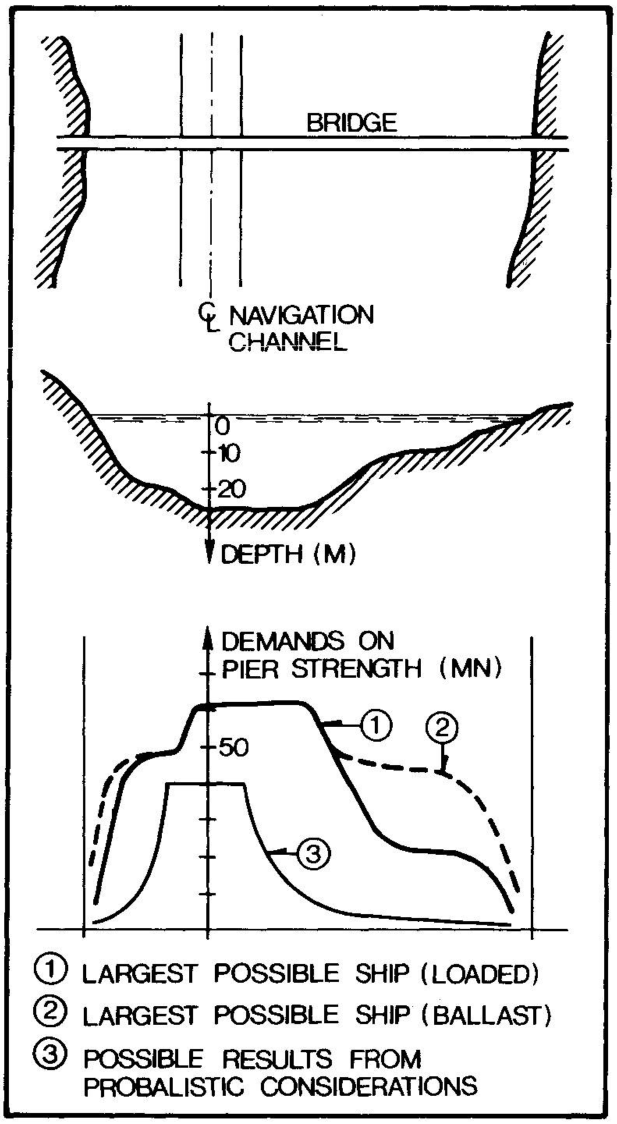
ZUSAMMENFASSUNG

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.



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.

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).

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.

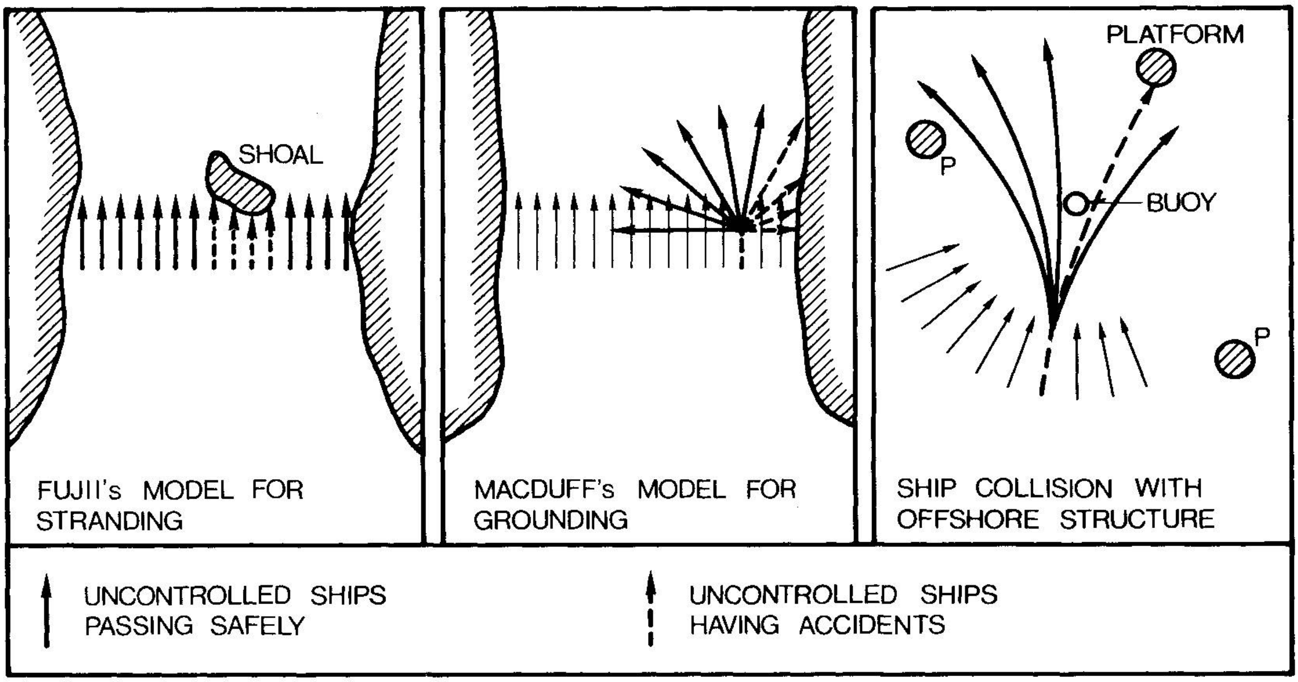


Fig. 2. Illustration of models for assessing the risk of accidents according to Fujii [1] and Macduff [2], and of collision with offshore structures [6].

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

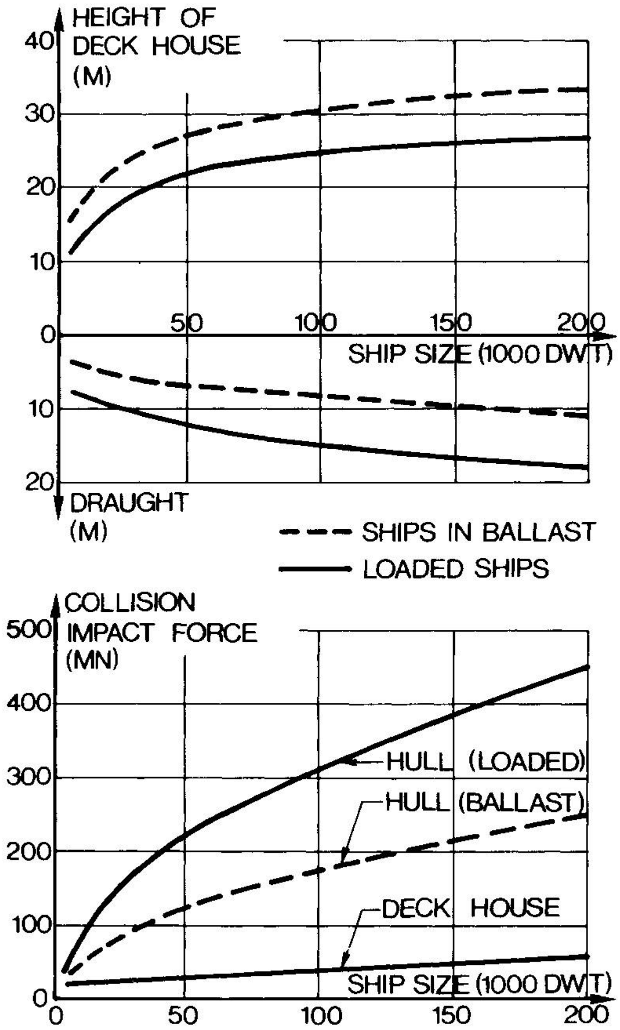


Fig. 3. Typical height, draught and collision impact forces of tankers.

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].

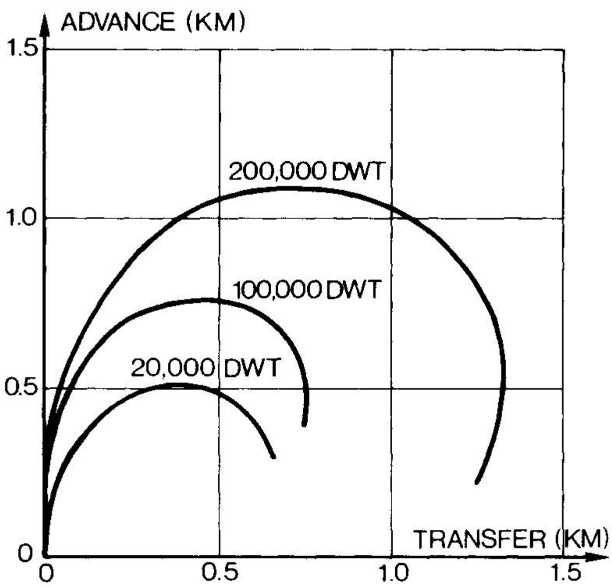


Fig. 4. Example of turning track dimensions for various tanker sizes (initial speed : 16 knots).

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.

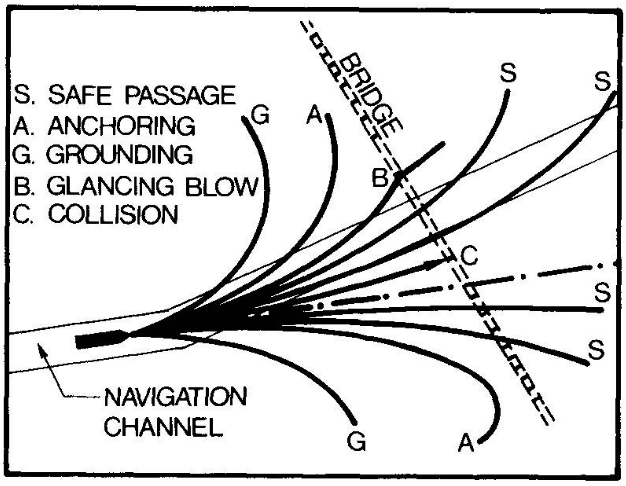


Fig. 5. Possible tracks of a ship out of control.

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 causation probability. 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 geometric probability. 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.

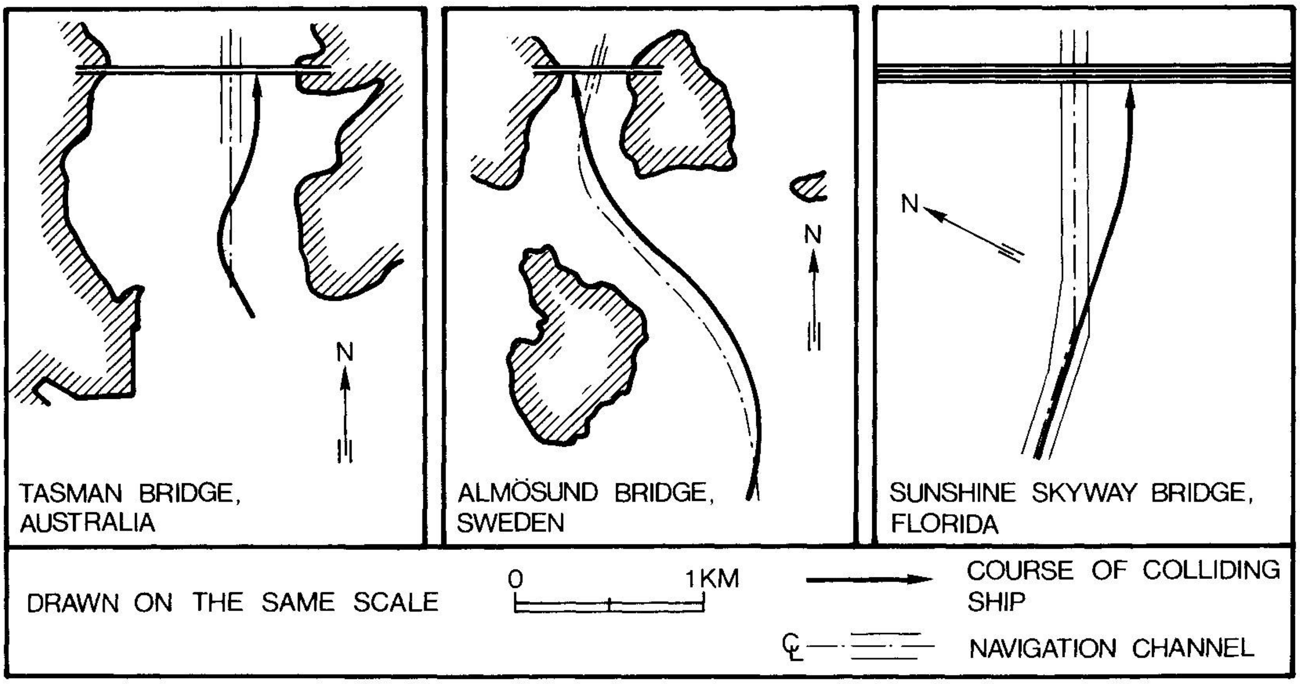


Fig. 6. Course of ships involved in three major bridge collision accidents.

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.

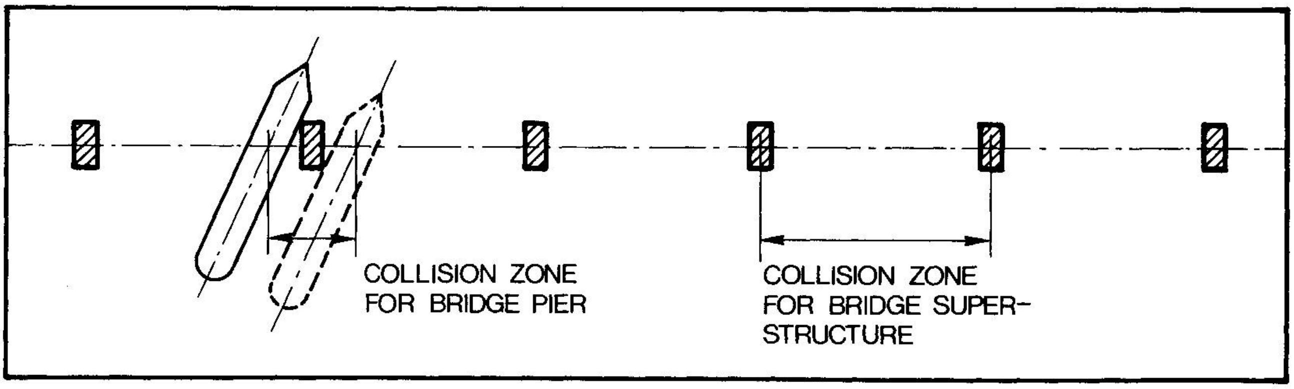
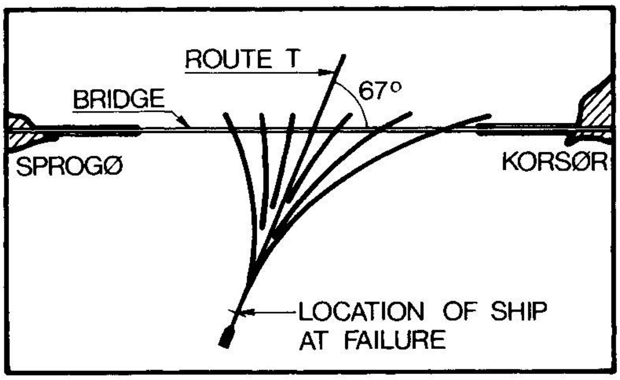


Fig. 7. Collision zones.

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 G^V

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 G^V 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.

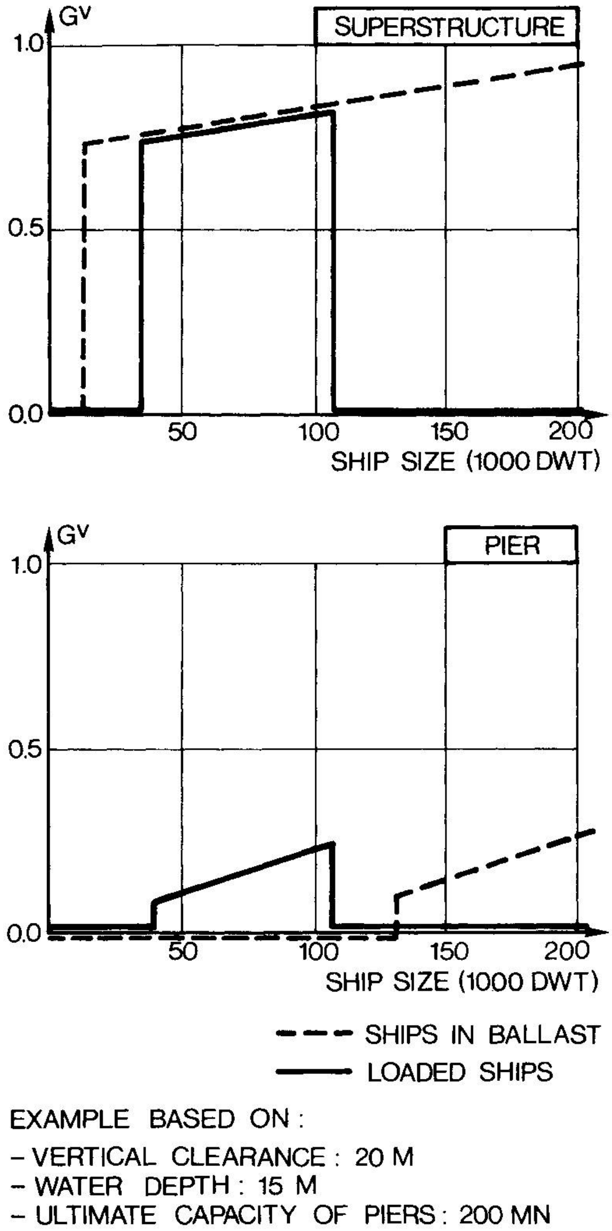


Fig. 9. Probability of destructive collision with a bridge pier or a bridge superstructure, as a function of the size of ship. (Imaginary example).

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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