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Models and methods of ship-bridge collisions risk assessment

Keywords

ship collision with bridges, safety on navigation, risk assessment

Abstract

The chapter presents methods and models used nowadays for risk assessment of ship-bridge collisions

1. Introduction

Bridges located over the navigable waterways could be threatened by the accidental impact of passing ships. The impact is caused usually by ships exit off the safe vertical or horizontal waterway borders. The bridge safety could be defined as its possibility to resist normal operational loads and the accidental loads of given ships collision loads. Many bridges especially historical ones are not designed to fulfil this criterion mostly due to extensive growth of ships capacities and its dimensions [30].

To evaluate the safety level of the bridges in respect to ships collision quantitatively, the risk concept is usually applied. The risk could be defined as combination of probability and consequences of given kind of accident.

Figure 1. Collision of m/s "Karen Danielsen" with West Bridge in Great Belt (3 march 2005, 1 fatality)

The area near the bridge is usually limited in two dimensions so the ship-bridge accident can be considered in horizontal and vertical aspect. Assessment of bridge risk in aspect of ship collision is very important and several national and international regulations and guidelines have been already developed [1], [2], [3], [22].

This chapter deals with the evaluation of ship and bridge safety by means of finding:

1. Probability of collision with bridge spans, piers and other bridge structures,
2. Most exposed places of collision on the bridge,
3. Possible consequences of such damage (ship, bridge, environment),
4. Methods of bridge protection (dolphins, guides, artificial islands etc),
5. Other methods of risk reduction (reporting systems, traffic regulations, marking etc).

There are several methods of bridge risk assessment in respect to ship collisions [22], [5]. The most important scientific methods used for safety evaluation of bridges in aspect of ship collision are:

1. Statistical methods based on accident databases.
2. Analytical methods.
3. Computer simulation experiments:
   a. real- and fast- time simulations,
   b. full-mission and simplified PC simulators.
4. Real experiments:
   a. GPS techniques,
   b. laser and total stations,
   c. photogrammetric researches.

The statistics of ship-bridge collisions are presented on *Figure 2*. *Table 1* presents most important casualties of accidents involving ships and bridges [5].

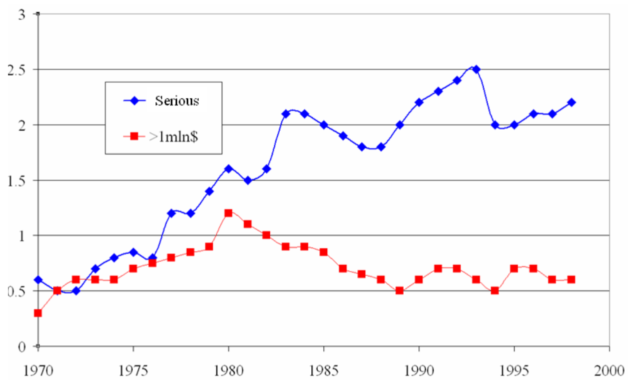

Figure 2. Accidents of ship-bridge collisions

Table 1. Fatalities in ship-bridge collisions (1960-2002)

Bridge	Year	Fatalities
Severn River Railway, UK	1960	5
Lake Ponchartain, USA	1964	6
Sidney Lanier, USA	1972	10
Lake Ponchartain, USA	1974	3
Tasman, Australia	1975	15
Pass Manchac, USA	1976	1
Tjorn, Sweden	1980	8
Sunshine Skyway, USA	1980	35
Lorraine Pipeline, France	1982	7
Sentosa Aerial Tramway, China	1983	7
Volga River Railroad, Russia	1983	176
Claiborn Avenue, USA	1993	1
CSX/Amtrak Railroad, USA	1993	47
Port Isabel, USA	2001	8
Webber-Falls, USA	2002	12

2. Navigational risk assessment of ship-bridge collision

Marine traffic engineering defines risk R as possibility of losses in given time and express as multiplication of accident probability and losses due to accident In case if many risk factors exists the total risk is expressed as following sum:

$$R = \sum_{i=1}^{n} P_i C_i \qquad (1)$$

where:
- P_i – probability of i-th accident in given time (i = 1, 2, ..., n),
- C_i – consequences of i-th accident in given time,
- n – number of possible accidents.

The risk assessment is the three stages as follows procedure (*Figure 3*):

1) hazard identification,
2) probability assessment,
3) consequence analysis.

To compare different systems and use tolerable risk criterions the measures of risk should be introduced. These measures could be divided as individual and group (societal) ones.

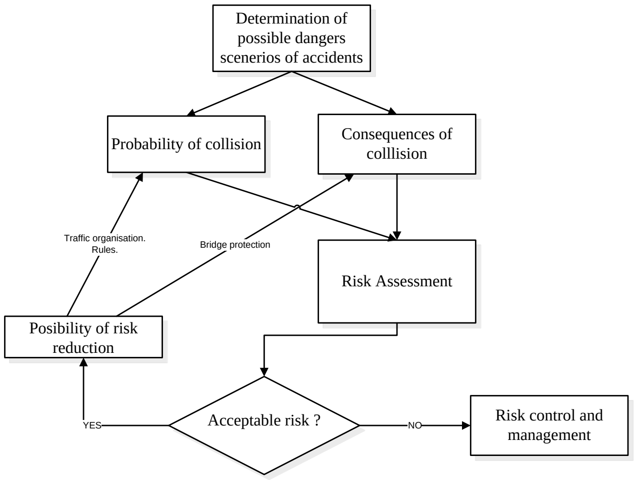

Figure 4. Risk assessment procedure for ship collision with bridges

2.1. Individually accepted risk (R_{ai})

Risk individually acceptable is accaptable probability that individual person being involved in risk activity will be accident with fatal consequences. It could be expressed as [34]:

$$R_{ai} = P_a P_{a/s} \leq \beta_i 10^{-4} \qquad (2)$$

where:
- P_a – probability of accident per year,
- $P_{a/s}$ – probability of death in case of accident,
- β_i – factor of individual risk (for example: 0,01 for factory work, 1 for car driving, 100 for mountain climbing).

2.2. Societal acceptable risk (R_{ag})

The societal acceptable risk is tolerable probability that in consequence of given accident certain amount of fatalities will be present. The regulations according tolerable risk are based on *FN*–curves (*Fatality Number*), which shows three regions bordered by two curves in logarithmic scale (*Figure 4*). The curves are accaptable risk higher where risk could be accepted, lower where risk could not be accepted and model where ALARP (*As Low As Reasonably Practicable*) where all possible measures should be undertaken to reduce the risk The F-N criteria curves could be expressed as: [34]

$$R_{ag} = 1 - FN(n) = P(N > n) \leq \frac{C_i}{n^{\gamma}} \qquad (3)$$

where:
$1\text{-}FN(n)$ – probability of accident with at least n fatalities,
C_i – accaptable probability for $n = 1$,
γ – factor of F-N curve slope varied form 1 to 2.

The slope of curves is described by coefficient γ. Neutral value is assumed as $\gamma = 1$, the $\gamma > 1$ could be assumed as averse for risk with accident with large number of fatalities but with small probability are less accepted than accidents with less number of fatalities.
The logarithmic coordinates are often criticised. The exception are Australian guidelines ANCOLD [17], where the criteria lines are curved to top in their middle areas. *Figure 4* presents ALARP areas used in Netherlands [25] and Great Britain [18]. The difference is slope of curves which shows different relation to accidents with high rate of fatalities.

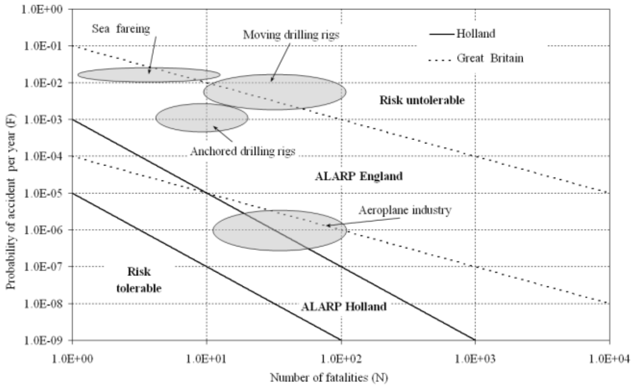

Figure 4. FN-curves and ALARP regions for England and Netherlands (based on [35])

3. Methods of collision probability assessment

Table 2 presents the most important methods applied for determination of probability of considered category of accidents. The methods differ significantly between each other and application of them is dependent of the given situation and cost of researches [6].

Table 2 Limitation and area of application of the probability estimation methods

Method	**Area**	**Accuracy**	**Cost***
Analytical	no limitation	low	low (1)
Empirical	no limitation	medium/ low	low (1)
Statistical	no limitation	medium/ low	medium (1)
Simulation researches			
Real time ship manoeuvring simulation	port area	high	high (10)
Fast time ship manoeuvring simulation	port area	high	medium (4)
Traffic stream simulation	coastal area, port area	medium	medium (2)
Generalized methods	port area	medium	low (1)
Real experimentations (observations)			
GPS	port and coastal area	0.1m to 3m	high (2)
Laser based methods	port area	0.1 m	medium (2)
Photogrammetric	port area	0.1m to 1m	low (1)
Radar methods	coastal area, port area	>15m	high (2)

*in parentheses the approx. number of personnel necessary in given method is presented.

3.1. General model of ships collision on restricted waters

The assumption of this model is that ship moves along predefined route x (*Figure 5*) with following probability of accident:

$$P_{AW} = P_{SA/A} P(Y \geq y_{MAX}) = P_{SA/A} \int_{y_{MAX}}^{+\infty} f(y)dy \qquad (4)$$

where: $P_{SA/A}$=conditional probability of serious accident, $f(y)$=the distribution of ships position, y_{MAX}=distance from to the centre of the waterway (route) to the waterway border.
Probability of serious accident $P_{SA/A}$ could be defined by the Heinrich ratio (coefficient of serious accident) or detailed consequence analysis. One of the most important stages of accident probability evaluation is statistical analysis of the results. The probabilistic concept of safety manoeuvring area is presented in *Figure 5*. The distributions are strongly dependant of waterway area arrangement and could be evaluated in simulations and validated in real experimentations.
Very important factor in MTE researches is determination of statistical distribution which describes position of manoeuvring ship (*Figure 5*). The statistical model of ships position in restricted areas depends of many factors. Usually the normal distribution function is applied when no detailed data available [6]. The other common applied distribution functions are:
– uniform [5],
– mixture of normal and uniform,
– other asymmetrical for example Rayleigh, Weibull, exponential, extreme value etc. [20].

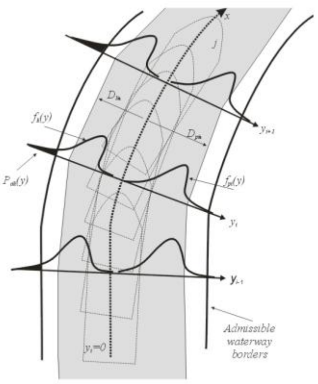

Figure 5. Probabilistic concept of safe manoeuvring area determination on the waterway

3.2. Empirical methods

Empirical methods are widely used especially in consequences assessment. The results achieved are significantly limited to data possessed and accuracy is quite low.

3.3. Simulation methods

Simulation methods are most popular and accurate at the moment. The most important method in determination of ships collision probability is wide range of model experiments. The most important simulation methods are:

1. methods applying real models of the ships,
2. methods applying computer models of the ships:
   a. real time manoeuvring simulators (man in the loop),
   b. fast time manoeuvring simulators (with computer model of the navigator),
3. ship traffic stream computer models,
4. Monte Carlo models.

The accuracy depends of the desired in researches level of adequacy. Sometimes the simplified models are more suitable for researches due to cost and time of preparation.

3.3.1. Ship maneuvering simulations

The most important elements of these models are hydrodynamic model and visualization of environment. Usually models assure full interaction with environment and give possibility to simulate following effects:

– thrust and side force of propellers,
– rudder forces,
– thrusters forces,
– current, wind and ice forces,
– canal and bank effects,
– mooring line, anchor, fender and tugs forces.

Figure 6. 3D projection visualisation, multi task ship bridge simulator

One of the most important factors in simulation models is the visualization of navigational situation. There are two main types of visualization:

– projection view, 3D view simulated on one or more screens (*Figure 6*),
– panoramic view (bird eye view), the visualization of the simulated scene similar to electronic chart system (*Figure 7*),

3.3.2. Monte Carlo simulations

There are four main groups of research problems in marine traffic engineering which could be solved by means of Monte Carlo (MC) method:

1. methods based on generalized results of simulation and real experiments [20],
2. stochastic models of traffic streams based on MC simulation [15],
3. the methods of uncertainty analysis for under keel clearance evaluation with application of MC simulation [12], [32].
4. fast time simulation models with stochastic external disturbances [19].

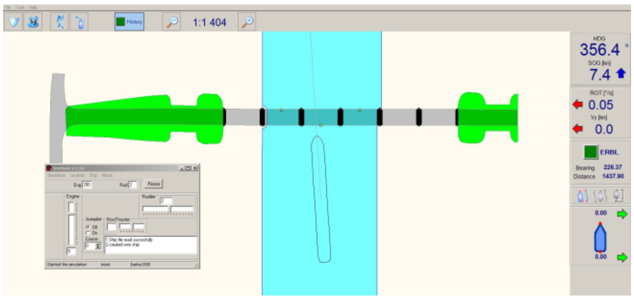

Figure 7. Panoramic visualization with simplified simulated control devices and electronic chart (single task simulator)

4. Consequence assessment

The ship bridge accidents could be divided on three kinds (*Figure 8*):

1. bow collision with bridge pillar,
2. side collision with bridge pillar,
3. deckhouse (superstructure) collision with bridge span.

The most important and frequent in scope of energy distributed during collision are bow collisions.

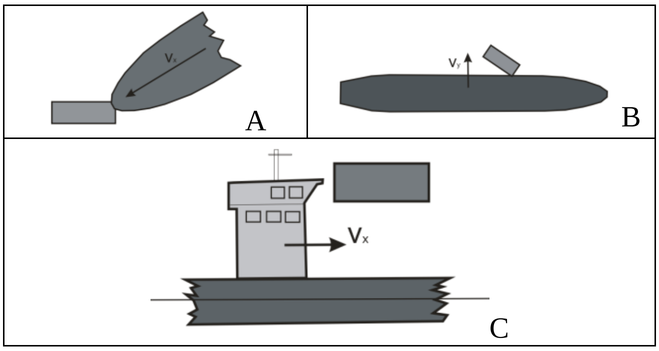

Figure 8. Three kinds of ship – bridge collisions (A-bow collision, B-side collision, C-deckhouse collision)

The consequences of ship-bridge collision depend of several factors like:

1. ships energy which depends of ship mass, speed and kind of impact,
2. energy absorption of ships by its structural destruction,
3. energy absorption of bridge elements.

There are several methods of ship impact energy calculation. Some of them are used for berthing equipment development like:

1. Girgrah [4] empirical method;
2. PIANC method [29];
3. polish guidelines for hydrotechnical structures design;
4. Vasco Costa method [33];
5. Peterson-Zhang method [28];

The load on the bridge during impact is most important factor in scope of consequences analyses. The load calculation methods could be divided on elastic with no structural deformations and elastic where structural deformations of ships hull are considered. The following methods could be applied:

1. empirical methods with structural damages consideration mainly based on Minorsky approach [26] with modifications [37];
2. empirical methods bases on experiments with ships models with structural damages consideration like Woisin method [36];
3. JCSS method [21] for maximal loads during impact with no consideration of structural damages;
4. Eurocode method [3];
5. German guidelines [2];
6. AASHTO method [1] for maximal loads during impact with no consideration of structural damages;
7. finite element methods;
8. Meier-Dörnberg method [24] of impact force determination;
9. other methods presented in Larsen [22].

The load P on the bridge during bow impact and sea speed could be calculated by Norwegian simplified formula [22]:

$$P = 0{,}5(DWT)^{1/2} \qquad [MN] \tag{5}$$

where: DWT- ships deadweight [ton]

Simplified formula for bulk-carriers (speed ab. 8m/s) [36] could be used for very approximate calculations:

$$P = 0{,}88(DWT)^{1/2} \pm 50\% \quad [MN] \tag{6}$$

Deformation of ships hull could be calculated as [1]:

$$l = 3{,}1(\sqrt{1 + 0{,}13E} - 1 \qquad [m] \tag{7}$$

where E- energy before impact [Nm]

when l<0,1m then elastic Meier-Dörnberg [24] formula could be used:

$$P = 10{,}95\sqrt{E} \qquad [N] \tag{8}$$

In case of plastic deformation AASHTO method (l>0.1m):

$$P = 5\sqrt{1 + 0{,}13E} \qquad [N] \tag{9}$$

Speed of ships could be considered by Woisin based on Minorsky [1959] uses empirical formula:

$$P = v^{2/3}(L^2 / 1100) \qquad [MN] \tag{10}$$

where: L-ships length [m], v –speed [m/s].

Woisin experiments [36] lead to empirical formula with speed of ships consideration:

$$P = 0.98(DWT)^{1/2}(v/8) \qquad [MN] \tag{11}$$

5. Methods of bridge protection

To mitigate consequences of ships impact and to protect the bridge pillars several methods could be considered. Those methods could be divided on two

with ships size consideration. The methods used for small and medium size ships of length less than 100m and small speeds during passage are as follows:
- guides,
- guide fenders,
- fenders,
- dolphins.

Bridge protections for large ships of length more than 100m and sea speed could be divided as follows:
- dolphins and group of dolphins,
- artificial islands,
- anchored steel wires,
- floating pontoons.

The use of given method is also dependant of depth where bridge pillars are located. The artificial islands are more reliable but could be located on less than 20m depth.

6. Case studies

In this section several case studies have been presented to illustrate the chosen problems for determination of layout of bridges protection and to assess the risk of collision with ships.

6.1. Determination of layout of guide fenders in Szczecin Railway Bridge by means of simulation and photogrammetric method

This case study [10] presents new method of ship passage under the bridge safety evaluation. The method is combination of photogrammetric real time measurements and simulation method. The photogrammetric method is applied in purpose to obtain real data of manoeuvring ships and barges and validation of simulation data. The results achieved by presented method can be applied for evaluation of safety of existing and modernized bridges in aspect of collision with passing ships. The method can be also used for determination of protection guide fenders for minimizing the possible ship's impact and increase the bridge construction safety. The paper presents case study of method application aimed to find optimal shape of guide fenders in Railway Bridge located in Szczecin. The Railway Bridge is located in Szczecin on West Odra River (*Figure 9*).

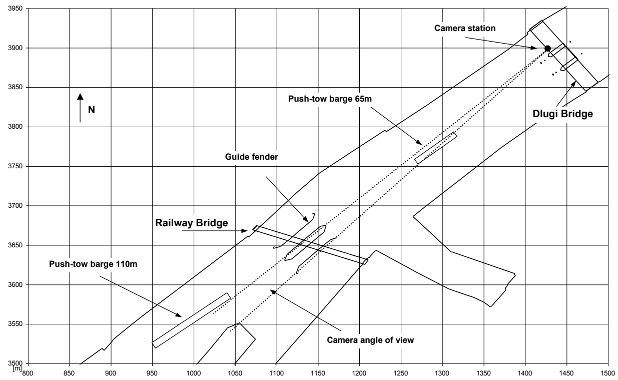

Figure 9. Layout of investigated area. Location of camera

Simulations have been performed by ship captains having experience in manoeuvring of analysed ships. Six simulation trial sets have been executed in extreme wind and current conditions. The simulations have been performed on simplified PC simulator (*Figure 10*). Following ships have been analysed: Bizon push-tow of 110m length, BM500 motor barge of 57m length and Adler River passenger ship of 53m length.

Figure 10. Simplified PC based computer simulator interface of investigated ships and area

The results of statistically worked out simulation trials for one simulation series of Bizon push-tow are presented in *Figure 11*. Swept path of ships (mean, maximal and 95% confidence) in given simulation series are presented.

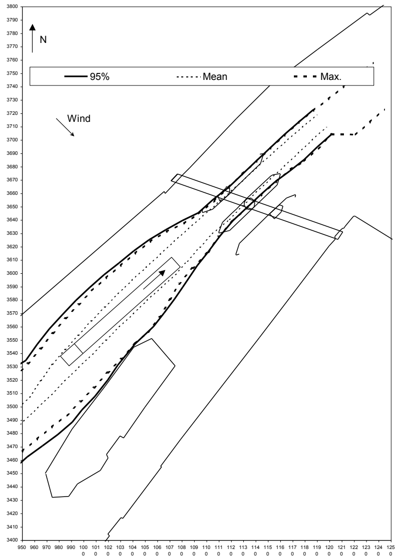

Figure 11. Results of 15 simulation trials of 110m push-tow Bizon (maximal, mean and 95% confidence swept paths)

The photogrammetric researches have been performed with use of off-the-shelf digital camcorder Panasonic NV-DS11 MiniDV, equipped with 1/4 inch CCD with 0.57 Mpixel. Lens with zoom 20:1 and focal length: 3.8-76.0 mm. To capture images from camera Matrox frame-grabber has been used. The location of the camera is presented on *Figure 9*. The camera has been located so to its axis has been directed towards the Railway Bridge. The approximate position of the camera has been found by performed control survey on location place. The approximate rotation angles have been obtained with use of area maps. The 4 coplanar control points located on bridge span have been used (*Figure 12*). Each passage of investigated ships has been recorded on tape and sequence of images has been grabbed later on.

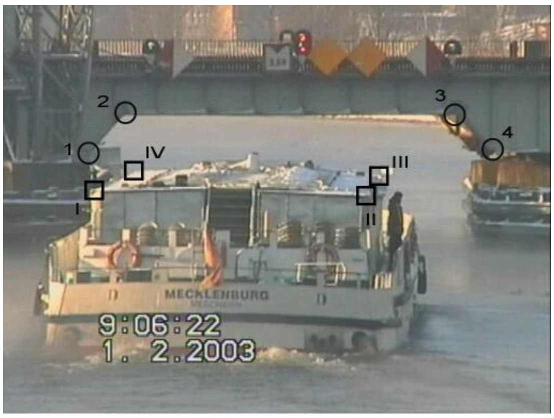

Figure 12. Localisation of control points (1, 2, 3, 4) and object points (I, II, III, IV)

The investigated ships belong to German owner Adler Schiffe, they are passenger barges Adler River and Mecklenburg with main parameters: L=53m B=8.08m, T=1.26m. The example photogrammetric reconstruction of one ship passage under the bridge with use of above presented model is shown on *Figure 13*. The reconstructed passages have been used to find swept path of ships in analysed conditions, to validate simulation results and to adjust manoeuvre tactics in simulations.

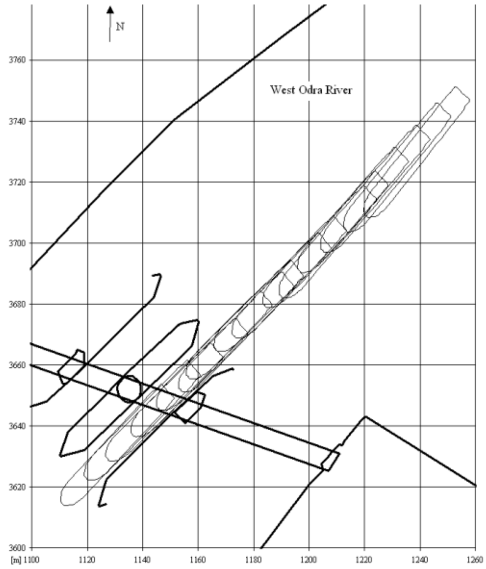

Figure 13. Photogrammetic reconstruction of ships passage under the Railway Bridge

The simulations and real time experiments enabled to design optimal and safe layout of new guiding fenders (*Figure 14*).

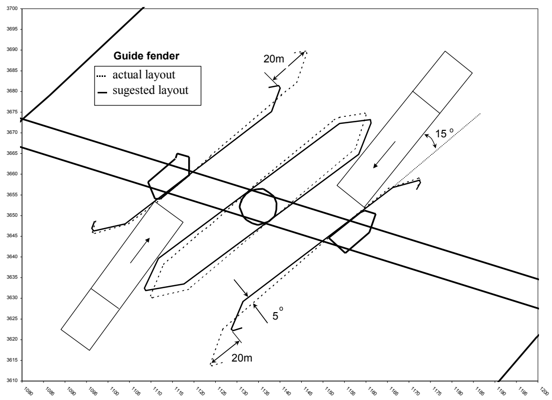

Figure 14. Optimal layout of guide fenders

6.2. Determination of possible loads of ships collision on proposed bridge piers located on Świnoujście-Szczecin waterway

6.2.1. Introduction

This case study [14] presents method of planned bridge, located on Swinoujście-Szczecin waterway, safety evaluation with respect to possible collision with passing ships (*Figure 15*). The method is a combination of three separate methods: real time ship manoeuvring simulation and Monte Carlo method combined with analytical method. First method is used to determine the probability density function of ship position during passage near the bridge piers and distributions of ship speed and courses. During simulations, human operators are used and thus the method takes into account human factor. Monte Carlo method is used in last step for extending the results over the bridge lifetime and possible meteorological conditions during bridge operation. It applies the previously determined distributions of ships positions that allow assessing probabilities of collision with bridge pier. The calculation of ships collision load and energy that are necessary for further consequence analysis is made on the base of distribution of ship speed obtained in simulations.

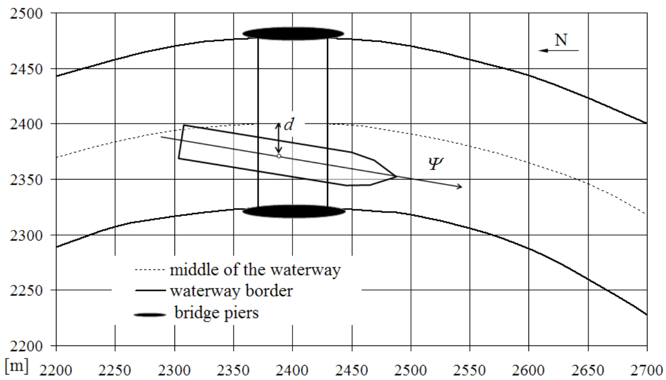

Figure 15. Investigated waterway area with planned bridge piers and simulated ships contour

6.2.2. Methodology of researches

The method is combination of three separate methods: real time ship manoeuvring simulation, analytical method of impact determination and finally Monte Carlo method. The real time, non-autonomous ship manoeuvring simulation is used to determine the probability density function of ship position and course during passage near the bridge piers and distributions of ships speed. It employs human operators during simulations so the human reliability is propagated through the model. The distribution of ships positions and courses are applied for determination of the collision probability with bridge pier. The distribution of ships speed, position and course are input data for analytical methods that are used for calculation of ships collision force load and energy. They are applied in further step for consequence and risk analysis. Finally, Monte Carlo method is used for extending the results over the bridge lifetime and all possible meteorological conditions during bridge operation. The method can be validated by real experiments performed near existing bridges in order to adjust obtained in simulation distribution function to reality Such verification carried out by photogrammetric method has been presented in [10], [11] and by optical methods in [9]. The whole research procedure is presented on *Figure 16*.

Figure 16. The research methodology

6.2.3. Researches

The most important distributions applied in presented case study are:

1. distribution of ships positions (centre of gravity and extreme starboard and port points of ships waterline) in respect to centre of the waterway,
2. distribution of ships courses,
3. distribution of ships speed (longitudal, vertical and angular).

Simulations are usually conducted in series in different meteorological conditions, each consist of several trials. Usually the distances of ships points from centre of the waterway can be well described by normal distribution. The example of such distribution for one of the simulation series is presented in *Figure 17*.

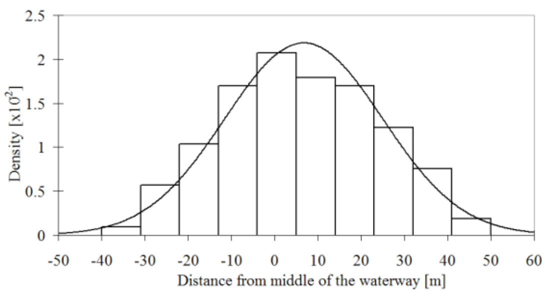

Figure 17. Histogram of the ship centre of gravity distances from the waterway centre fitted to normal distribution

Distribution of ships courses is strongly correlated with ships positions referred to the middle of the waterway. It can be straightforwardly explained: the more the ship is away from the centre of the waterway the more the navigator changes the course to come back to the desired track. This phenomenon can be observed in *Figure 18*. To include such observable fact into the model it is proposed to use simply linear regression model. The course could be calculated by distribution of distance from the middle of the waterway by the regression formula (*Figure 18*) with use of previously calculated normally distributed regression error.

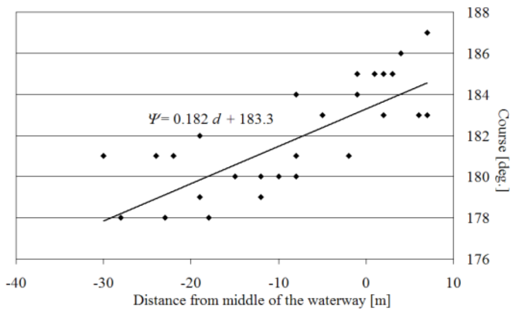

Figure 18. Linear correlation between distance from the waterway centre and ships course for one investigated simulation trial

Simulation scenery has been modelled in 2D environment. Simulation area layout is presented in *Figure 15*. The course of ship is denoted by *Ψ* and the distance from ships centre of gravity from centre of the waterway as d. The histogram of ships courses is presented in *Figure 19*. Although little skewness is observed due to bend of the waterway, the statistical tests of normality are positively verified on specified significance level.

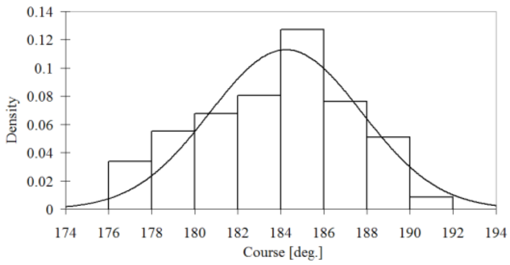

Figure 19. Histogram of courses fitted to normal distribution

Interesting results have been achieved after analysis of ship speed distributions (*Figure 20*). Due to special partition of engine inputs in model (same as on real ship) usually speed has been normally distributed but some ship captains and pilots kept speed between 4.25-4.5 m/s due to "half ahead" input on engine. Discrete distribution should be applied for modelling of such phenomenon in MC method. In other researches ships speed are often described by lognormal distribution.

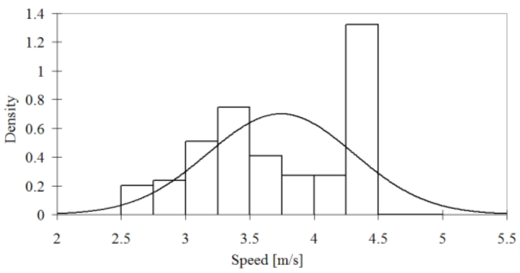

Figure 20. Histogram of ships speed fitted to normal distribution

6.2.4 Analytical methods of ship impact evaluation

In presented researches the impact force have been calculated by formulas adopted from JCSS [21]. The method assumes that the colliding ship is modelled as an elastic single degree of freedom system with stiffness equivalent k and mass m. The maximal possibly resulting interaction can be expressed by longitudinal (*Fx*) and vertical (*Fy*) force of impact and calculated as follows:

$$F_x = \mu F_y$$
$$F_y = \sin \alpha v \sqrt{km} \qquad (12)$$

where v = ships velocity of impact [m/s]; k = ship equivalent stiffness [MN/m]; m = mass [ton];□ μ = friction coefficient between hull and the structure; α = angle of impact;

Figure 21 presents the forces of impact during collision of ship with bridge piers at speed v and angle *α*.

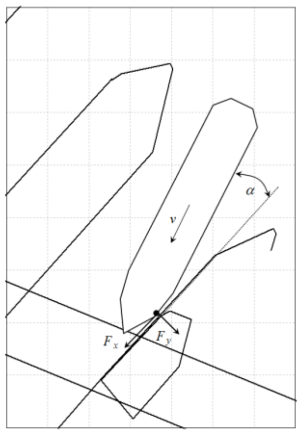

Figure 21. Impact forces during collision with guide fenders of the bridge.

6.2.5 Monte Carlo method

Monte Carlo method has been used in final step for evaluation of force load and probability of collision in single passage of given ship. One sampling MC epoch consists of following stages:

1. determination of navigational conditions,
2. selection of appropriate distributions,
3. determining ship position on the waterway,
4. determining ship course in dependence of position,
5. checking of collision with pier condition,
6. determining of ship speed,
7. determining of collision load.

6.2.6. Results

Real time simulations have been performed with use of 196 meters length, 28 meters breadth computer model of single propeller tanker. The simulation researches consist of 5 series in different wind and current conditions. The following conditions have been modelled:

1. no wind and current conditions,
2. contrary current 1m/s,
3. positive current 1 m/s,
4. wind E 15m/s,
5. wind E 15 m/s and contrary current 1 m/s.

Each series consists of 30 trials, which is the number that guarantees proper statistical accuracy. Monte Carlo runs have been divided in 10 series each for 200000 iterations. Such approach guaranteed statistical convergence of achieved results. The *Figures 22* and *23* present distribution of collision load on starboard and port pier of the bridge. There is significant difference between distributions of collision load in both sides especially in the shape of distribution. Collision force load on bridge pier located on starboard side of waterway is symmetrical and normally distributed. Collision force on the port side pier has considerable positive skewness (*Figure 23*). Such information could be very useful for designing and protection of the pier. Probabilities of collision in single passage of given kind of ship are as follows:

- 7.7 × 10-3 for starboard pier,
- 1.6 × 10-3 for port pier.

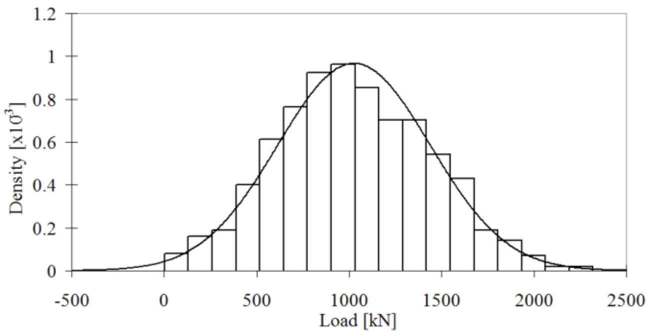

Figure 22. Distribution of collision load on starboard bridge pier fitted to normal distribution.

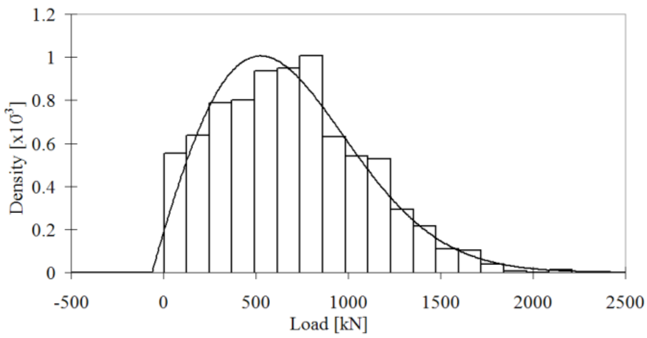

Figure 23. Distribution of collision load on port bridge pier fitted to three parameter Weibull distribution.

6.2.7. Conclusions

The method due to its complexity can be applied for all kind of bridges and ships manoeuvring in any conditions. The most expensive part of it related with real time ship manoeuvring simulations is reduced to necessary minimum. The results obtained with the method presented are distributions of the collision force load on the bridge piers as functions of time. They can be in further step investigated and applied for risk assessment of bridge structure with use of bridge structural reliability assessment. The possible risk expressed for example as human fatalities can be further investigated based on presented results with knowledge of distribution of number of people presented on the bridge during ship collision with assumption that bridge will collapse after accident.
The method could be useful for optimal design of the bridges and its protections and for the modernization and safety assessment of existing bridges. The method considers only the most typical ship bow-bridge collisions and assumes that dimension of pillars is much smaller than the ship itself.

6.3. Determination of layout of guide fenders in Elblag Port

6.3.1. Assumptions

The main aim of analyses has been to design optimal and safe new fender guides for moderijsed two bridges in Sea Port of Elblag (called Lower and Higher see *Figure 24*). The modernization assumes the widening passage for ships up to 16m. The most important change is establishing the new hydraulic swing bridge machinery which will enable to operate higher ships than today.

Figure 24. Lower bridge in Elblag

6.3.2. Ships

The calculations of load have been done for maximum allowable inland ship of length 100m and breadth 15. Typical inland ships investigated in this researches is inland ship with own propulsion BM500-type of length 57m and breadth of 7.5m.

6.3.3. Determination of load on bridge piers

Meier-Dörnberg method [24] has been applied as typically for inland ships for determination of load of the characteristic ships. The most frequent scenarios have been selected as the most important for fenders and piers design: 1). frontal collision of maximal ship (*Figure 25*), and 2). side collision with 20 degrees angle (*Figure 26*).

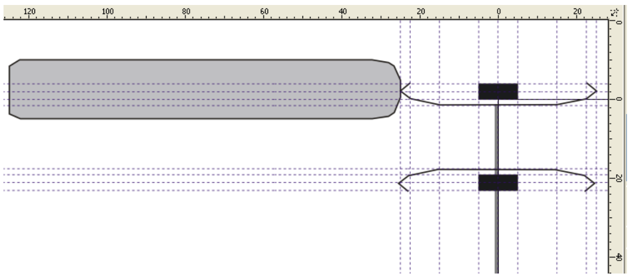

Figure 25. Collision of maximal ships with fenders

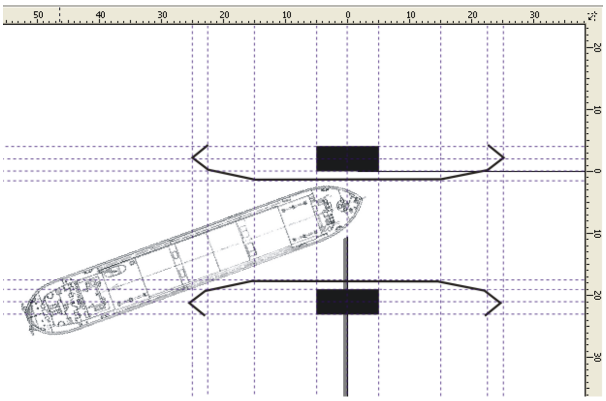

Figure 26. Collision of BM 500 with middle part of fenders with 20 degrees angle

Calculations leads to following conclusions:
1. maximal load force is 9.5MN during accidental collision of maximal ship with fender system,
2. the working load of maximal ship during passage is not exceeding 0.08MN,
3. maximal load of BM 500 in middle of fenders equals 0.92MN.

Table 2 presents load forces for maximal ships with different angles and velocities. Maximal load assumed for speed of 3m/s and 90 degrees angle.

Table 2. Load [MN] for maximal ships during impact

Angle	v [m/s]					
[deg.]	0.5	1	1.5	2	2.5	3
0	0.00	0.00	0.00	0.00	0.00	0.00
10	0.08	0.31	0.69	1.23	1.91	2.75
20	0.30	1.19	2.67	4.71	6.20	6.28
30	0.70	2.78	6.17	6.29	6.45	6.63
40	1.26	4.99	6.29	6.51	6.78	7.09
50	1.94	6.20	6.45	6.77	7.16	7.61
60	2.66	6.28	6.61	7.03	7.54	8.12
70	3.35	6.35	6.75	7.28	7.89	8.57
80	3.92	6.41	6.87	7.47	8.17	8.93
90	5.03	6.52	7.10	7.84	8.68	9.59

The method applied enables to determine also deformation of ships hull. The deformation in function of speed and impact angle is presented in *Figure 27.*

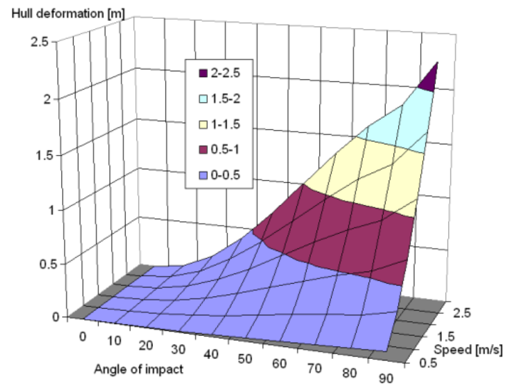

Figure 27. Deformation of maximal ships hull during impact on different angles

6.4. Real experiments for determination of ship passage safety under the Dlugi Bridge in Szczecin

The Dlugi Bridge is historical bridge located in Szczecin. Two brick piers are enabling navigation for inland ships of up to 18m breadth (*Figure 28*). Bridge opening mechanism is not operable nowadays.

Figure 28. Dlugi Bridge in Szczecin

Presented method of safe area determination [9] is based on real measurements with use of one laser rangefinder placed on shore. The distance has been measured to one side of ship only. The second side position has been estimated with use of mathematical models. The measurement tool enables to repeat measurements with 1Hz frequency which gives opportunity to reconstruct the passage in time (*Figure 29*).

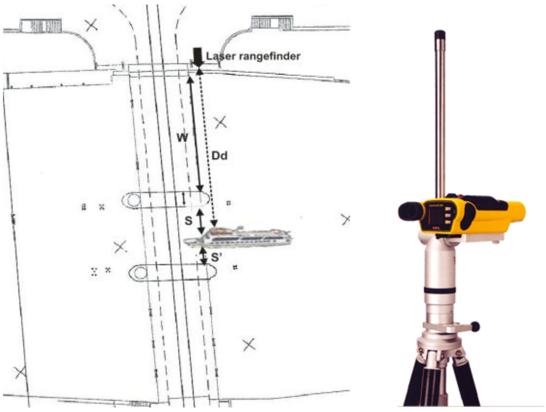

Figure 29. Layout of investigated area and mirrorless laser range finger used in researches

The method is restricted to very short legs of waterways (up to vessels length). Single record of passage of Meckelnburg inland passenger ship is presented in *Figure 30*. During measurement the wind and current conditions have been recorded. In case the ship is turning during passage distance is changing (*Figure 30*).

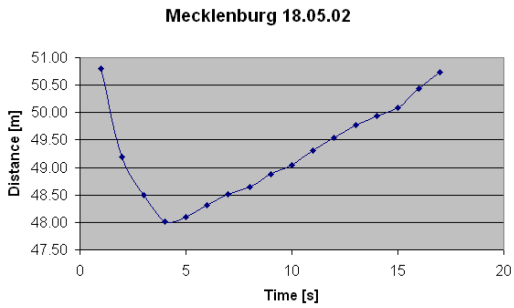

Figure 30. Recorded passage of one investigated ship

Three similar inland passenger ships have been investigated (Adler Steamer, Adler River and Mecklenburg) of length around 53m and breadth 8m. More then 25 passages of ships been recorded in researchers. *Figure 31* presents recorded and mathematically reconstructed passages of ships during navigation under the Dlugi Bridge.

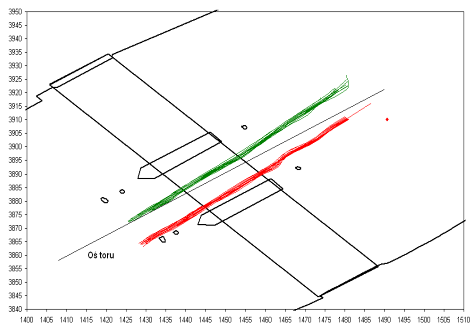

Figure 31. Reconstructed passages of 25 inland ships

The histogram of distances to one of investigated piers is presented in *Figure 32*. The results could be used for probability assessment of collision of ships with pier and risk assessment of ships bridge collisions.

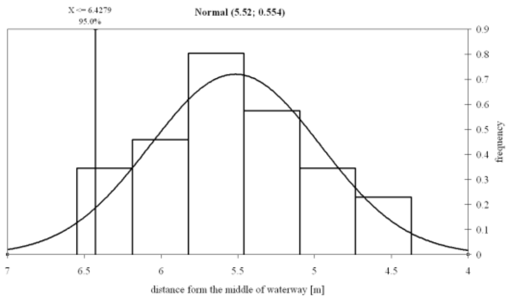

Figure 32. Histogram of distances of ships side to the pier fitted to normal distribution

7. Conclusions

The possible collision of ships with the bridges on navigable canals could be catastrophic in consequences. It enforces the necessity of full range of available methods application to determine the risk and protect the bridges against accidents.

Presented chapter describe whole range of nowadays knowledge about ship-bridge collisions problems necessary for practical risk assessment and guidelines of bridge protection.

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