

METHODS OF SHIP-BRIDGE COLLISION SAFETY EVALUATION

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ABSTRACT

The paper 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 [Proske & Curbach 2003].

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 [AASHTO 1991, E DIN 1055-9 2000, ENV 1991–1 Eurocode 1 1994, Larsen 1993].

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 [Larsen 1993, Gluver & Olsen 1998]. 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 [Gluver & Olsen 1998].

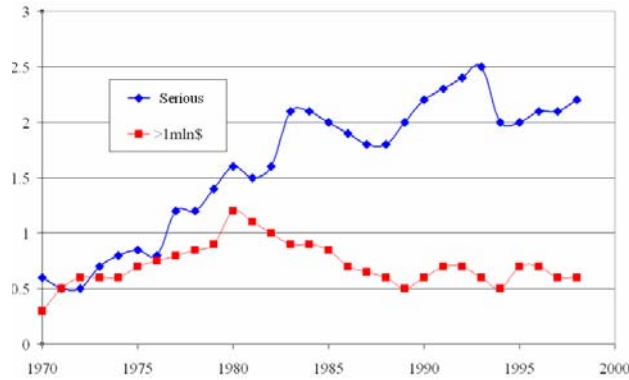


Figure 2. Accidents of ship-bridge collisions

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:

$$R = \sum_{i=1}^n P_i C_i \tag{1}$$

where: P_i = probability of i -th accident in given time ($i = 1, 2, \dots, n$); 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 (Fig. 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.

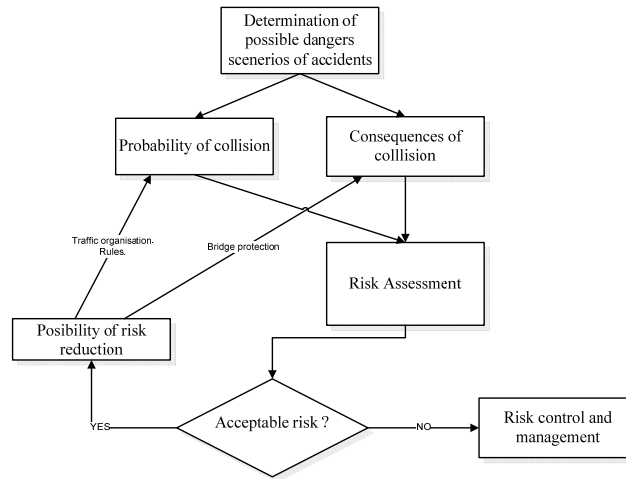


Figure 3. Risk assessment procedure for ship collision with bridges

2.1. Individually accepted risk (R_{ai})

Risk individually acceptable is acceptable probability that individual person being involved in risk activity will be accident with fatal consequences. It could be expressed as [Vrijling i Van Gelder, 1997]:

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

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 (Fig. 4). The curves are acceptable 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: [Vrijling i Van Gelder, 1997]:

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

where: $1-FN(n)$ = probability of accident with at least n fatalities; C_i = acceptable 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 [Heinrichs i Fell, 1995], where the criteria lines are curved to top in their middle areas. Fig.4. presents ALARP areas used in Netherlands [MHLUPE, 1988] and Great Britain [HSE, 1989]. The difference is slope of curves which shows different relation to accidents with high rate of fatalities.

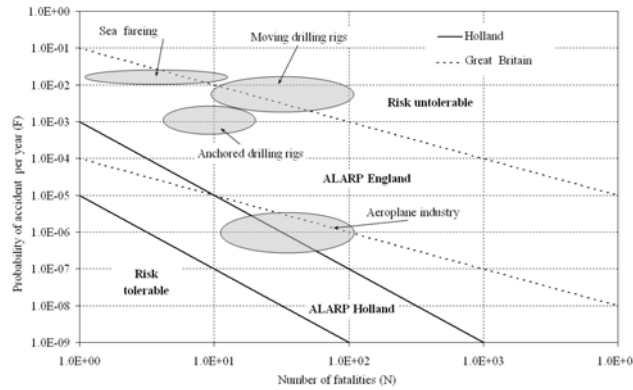


Figure 4. FN-curves and ALARP regions for England and Netherlands (based on [Whitman, 1984])

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 [Gućma 2005].

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:

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

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.

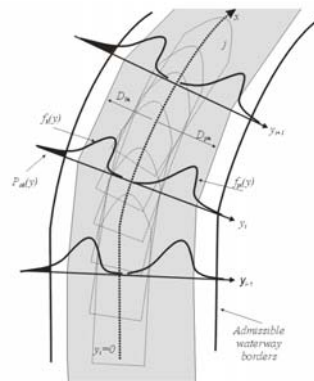


Figure 5. Probabilistic concept of safe manoeuvring area determination on the waterway

Very important factor in MTE researches is determination of statistical distribution which describes position of manoeuvring ship (Fig. 34). 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 [Gućma 2005]. The other common applied distribution functions are:

- uniform [Gluver & Olsen 1998],
- mixture of normal and uniform,
- other asymmetrical for example Rayleigh, Weibull, exponential, extreme value etc. [Iribarren 1999].

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 (Fig. 6),
- panoramic view (bird eye view), the visualization of the simulated scene similar to electronic chart system (Fig. 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 [Iribarren 1999, Gućma 2000],
2. stochastic models of traffic streams based on MC simulation [Hansen & Simonsen 2001, Grabowski et al. 2000, Gućma 2003, Gućma & Zalewski 2003],
3. the methods of uncertainty analysis for under keel clearance evaluation with application of MC simulation [Gućma 2004a, Sand et al. 1994].
4. fast time simulation models with stochastic external disturbances [Hutchison et al. 2003].

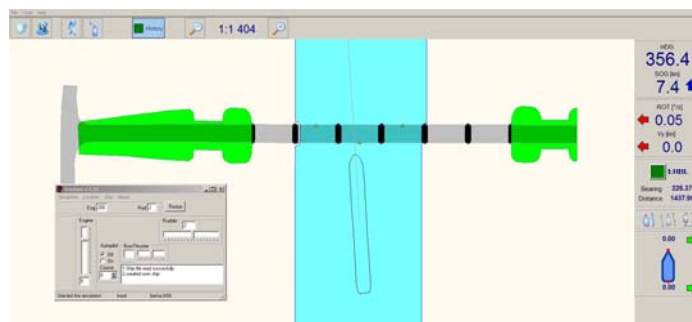


Figure 7. Panoramic visualization with simplified simulated control devices and electronic chart (single task simulator)

4. CONSEQUENCE ASSESSMENT

The ship bridge accidents could be divided on three kinds (Fig. 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.

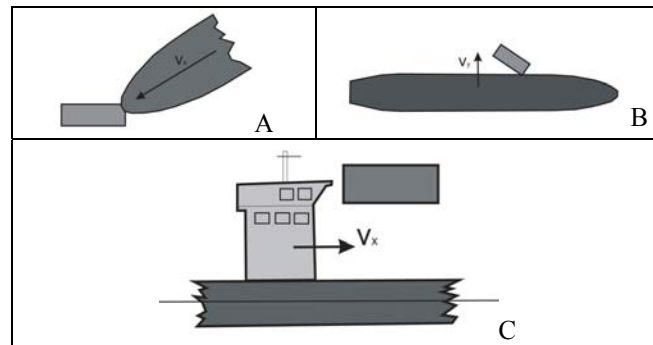


Figure 8. Three kinds of ship – bridge collisions (A-bow collision, B-side collision, C-deckhouse collision)

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 [Girgrah 1977] empirical method;
2. PIANC method [PIANC 1984];
3. polish guidelines for hydrotechnical structures design [Mazurkiewicz 1997];
4. Vasco Costa method [Vasco Costa 1969];
5. Peterson-Zhang method [Petersen i Zhang 1998];

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 [Minorsky 1959] with modifications [Zhang 1999];
2. empirical methods bases on experiments with ships models with structural damages consideration like Woisin method [Woisin, 1979];
3. JCSS method [JCSS 2001] for maximal loads during impact with no consideration of structural damages;
4. Eurocode method [ENV 1991–1 Eurocode 1 (1994)];
5. German guidelines [E DIN 1055-9 (2000)];
6. AASHTO method [AASHTO 1991] for maximal loads during impact with no consideration of structural damages;
7. finite element methods;
8. Meier-Dörnberg method [1984] of impact force determination;
9. other methods presented in Larsen [1993].

The load P on the bridge during bow impact and sea speed could be calculated by Norwegian simplified formula [Larsen 1993]:

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

where: DWT- ships deadweight [ton]

Simplified formula for bulk-carriers (speed ab. 8m/s) [Saul based on Woisin 1979] could be used for very approximate calculations:

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

Deformation of ships hull could be calculated as [AASHTO 1991]:

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

where E - energy before impact [Nm]; when $l < 0,1m$ then elastic Meier-Dörnberg [1984] formula could be used:

$$P = 10,95\sqrt{E} \quad [N] \quad (8)$$

In case of plastic deformation AASHTO method ($l > 0,1m$):

$$P = 5\sqrt{1 + 0,13E} \quad [N] \quad (9)$$

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

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

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

Woisin experiments [1979] lead to empirical formula with speed of ships consideration:

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

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 [Gućma 2003a] 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 (Fig. 9).

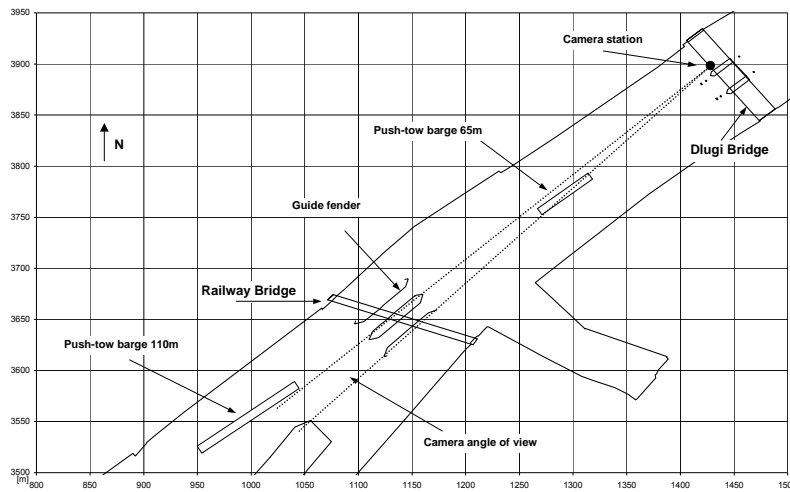


Figure 9. Layout of investigated area. Location of camera

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 (Fig. 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 Fig. 11. Swept path of ships (mean, maximal and 95% confidence) in given simulation series are presented.

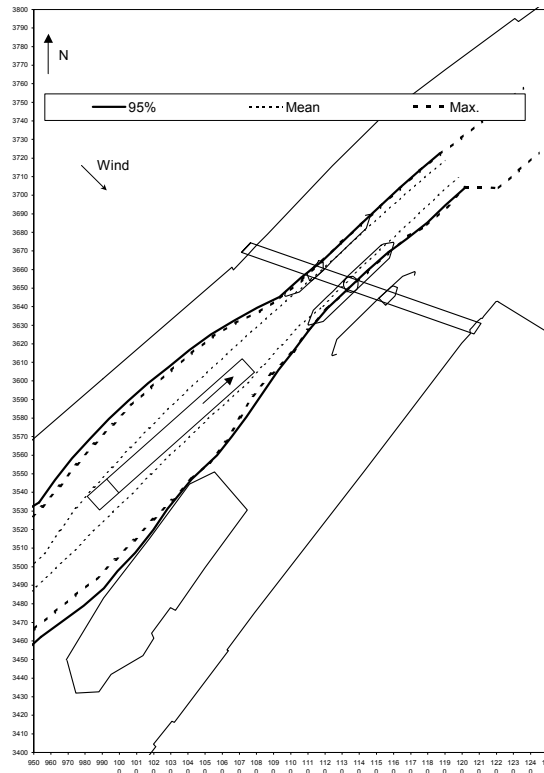


Figure 11. Results of 15 simulation trials of 110m push-tow Bizon (maximal, mean and 95% confidence swept paths)

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 Fig.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 (Fig. 12). Each passage of investigated ships has been recorded on tape and sequence of images has been grabbed later on.

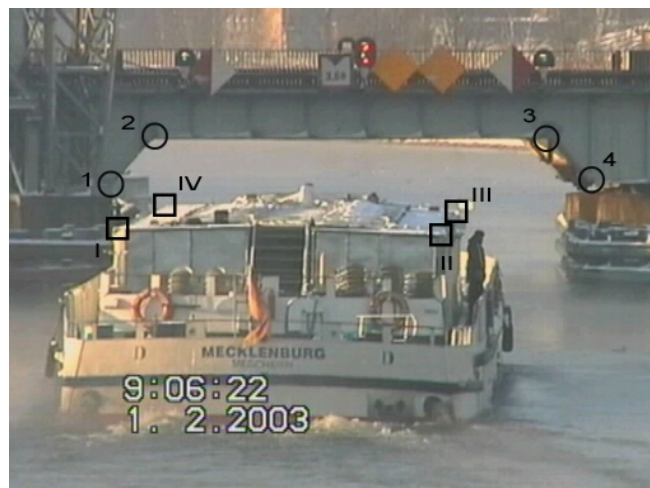


Figure 12. Localisation of control points (1, 2, 3, 4) and object points (I, II, III, IV)

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 Fig.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.

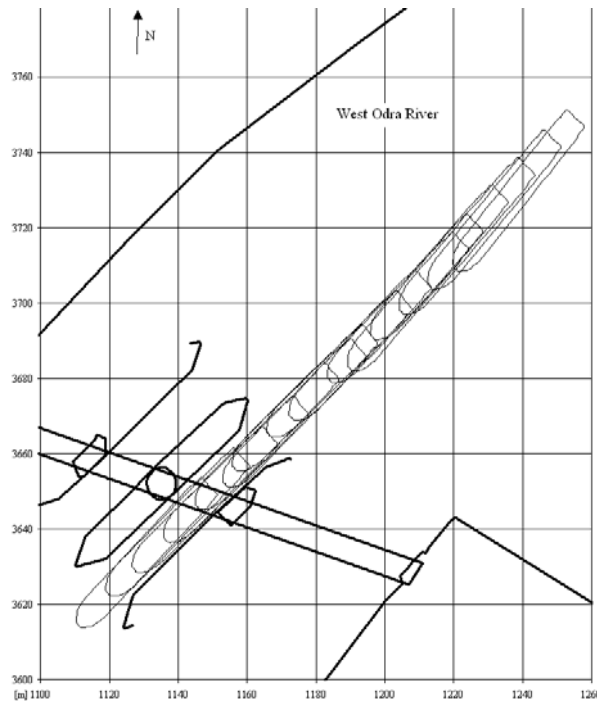


Figure 13. Photogrammetric reconstruction of ships passage under the Railway Bridge

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

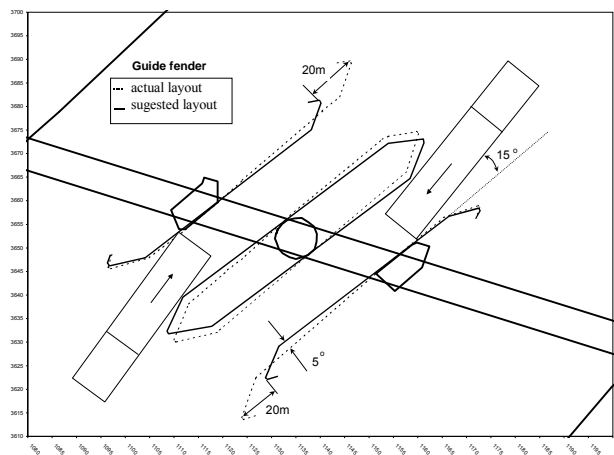


Figure 14. Optimal layout of guide fenders

6.3. Determination of layout of guide fenders in Elblag Port

6.3.1. Assumptions

The main aim of analyses [Analysis 2008] has been to design optimal and safe new fender guides for modernised two bridges in Sea Port of Elblag (called Lower and Higher see Fig. 14). 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 14. 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 [1984] 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 (Fig. 15), and 2). side collision with 20 degrees angle (Fig. 16).

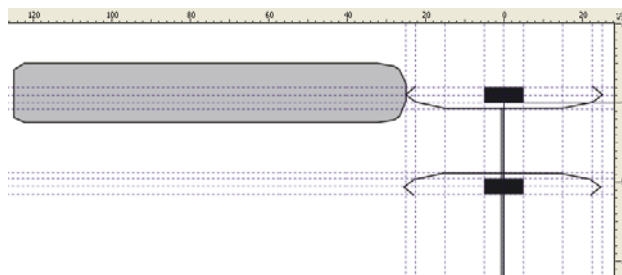


Figure 15. Collision of maximal ships with fenders

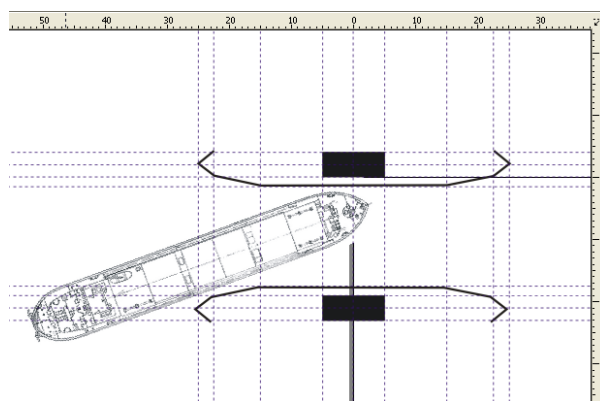


Figure 16. Collision of BM 500 with middle part of fenders with 20 degrees angle

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 [deg.]	v [m/s]					
	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 Fig. 17.

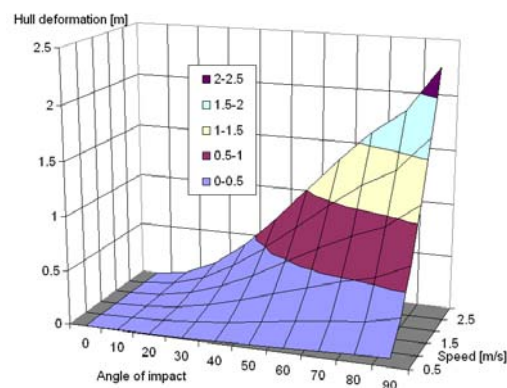


Figure 17. Deformation of maximal ships hull during impact on different angles

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

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