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Acceptable risk and probability of collision assessment in area of bridges in respect of ships collisions

Keywords

ship – bridge collision, bridge safety, bridge collapse, risk acceptability levels

Abstract

The paper presents selected problems of risk management in respect of ship collisions with bridges. Accident statistics in Poland and around the world are presented. Wide discussion on bridge collapse risk acceptance criteria have been carried out. Finally to different case studies of probability assessment taking into account both horizontal and vertical clearances.

1. The accident statistics and the problems of ships collisions with bridges

Bridges situated on sea and inland waterway areas belong is the particularly sensitive infrastructure from three the major causes:

1. create restrictions of not only in the vertical water area but also in horizontal;
2. they create the threat to its users in the case of ship-bridge collision and bridge collapse,
3. the cost of the bridge is usually considerably larger then the cost of the ship itself.

The ground analyses of the literature [4]-[5] it is clear that the collisions with ship is they of the major causes of bridges disasters and they can be even 30% of all reasons of whole bridge catastrophes. In years 2003-2013 the scientific the team of the marine traffic engineering of Maritime University of Szczecin executed the row of analyses of the safety of bridges in this [3]:

- the railway bridge in Szczecin (2003),
- two locations of foot bridges in Elbląg (2008),
- foot bridges to the Ołowianka Island in Gdańsk (2009),
- two bridges on the Motława in Gdańsk (2009),
- the bridge to the Ostrów Brdowski Island in Szczecin (2013).

The problems of ships collisions with bridges comes from years 60, when is in the result of the height of the intensity of the traffic and dimensions of ships followed the scale of events and disasters. First, sizable studies were done in the year 1980 after the allision of the ship Summit Venture with the bridge Sunshine Skyway. In monograph [3] it is presented the composition of several collisions of ships with bridges since the year 1980 together with results and reasons of collisions, the death rate and the name of the ship. One can notice (*Figure 1*) that averagely in the world it appear 2 serious collisions of ships with bridges per year, and every 2 years it appears the event with catastrophic results causing the destruction of the bridge, the loss of the ship or the fatalities.

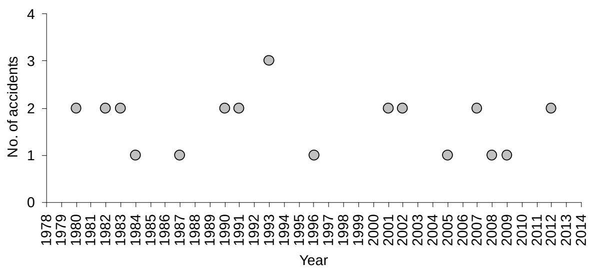

Figure 1. The yearly number of ships collisions with bridges serious in results in the world

American statistics [6] brought to light that the large part of collisions of ships with bridges caused however comparatively not large scale losses. In years 1992–2001 one noted together 2692 collisions. Only 61 from them (2,2%) caused greater losses then 0,5 millions USD. The 1702 events (63%) of them was incidents in which the damage were not significant and the repairs of the bridge was not necessary.

In the inland area administered by RZGW in Szczecin there was average one collision of the inland unit with the bridge per year. Most destructive was the collision in 2001 when the guides of the railway bridge in Szczecin was destroyed, what caused the necessity of their exchange. In the region administered by RZGW all cases of collisions of inland units with bridges Szczecin are presented in *Figure 2*. It was recorded 17 cases within analysed of 16 years. Happily, it never arrived to fatalities in people. Events due to error of the navigator dominates, they happens with the frequency approx. 90%, what confirm world statistics. Alarming is also the large participation of collisions with bridge spans which amounts around 65%. The part from them ended with bulky damages of the ship. Such collisions result most often due errors in the planning phase of navigational passage under the bridge, mostly from the ignorance about the current clearance of the bridge or the height of the air-draught of ship.

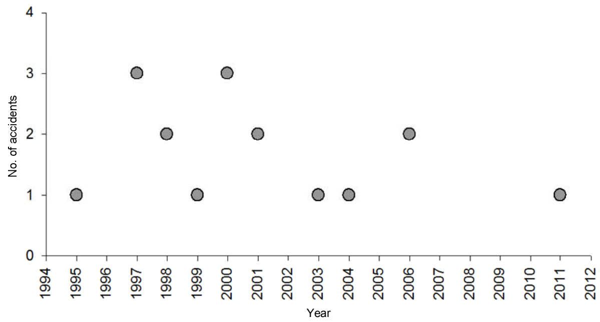

Figure 2. The number of events with bridges in the region administered by RZGW in Szczecin [3].

2. The risk management in the aspect of the collision with ships in the bridges area

The creation of the rational risk management system before the delivery of engineering construction, especially, when such object could attract possible fatalities, are nowadays the standard in many countries. In this chapter some theoretical and practical aspects of the risk management are presented. The important are the measures of the risk assessment what ties in with the settlement of levels of its acceptance. *Figure 3* presents the four main factors influent on collisions of ships with bridges. To navigational conditions need to be also considered.

The risk of the collision of ships with bridges one can divide on five main categories:

1. the risk for the owner of the bridge connected with necessity of its repair or the loss of profits after the break of the bridge passage;
2. the risk for users of the bridge connected with the possibility of the loss life, health's or the monetary values during the passage;
3. the risk for third parties which do not draw any advantages from the bridge. It refers also ships, in case, when the bridge causes the threat with relation to of the state before construction of the bridge;
4. the risk concerning of results socioeconomic because of the break of the passage;
5. the risk environmentally as result of pollution with the overflow or with the liberation of toxic gases.

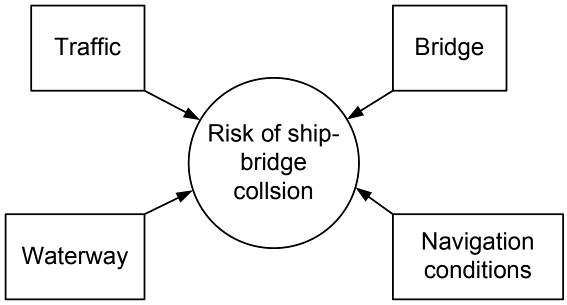

Figure 3. Factors of the risk of collisions of ships with bridges

When carrying out risk analyses in the area of bridges in the respect of the ship collision, the critical situation is defined as the unintentional collision of the ship with the bridge or with its structure. Such critical events one divide on [2]:

1. the collision of ships hull with piers,
2. the collision of the superstructure with the bridge pier or its protections.

Navigational accidents collision of ships with bridges one can divide on following categories:

1. Ships underway passing under the bridge which collide with the pier of the bridge as result of the error of the navigator.
2. Ships underway on the planned route passing under the bridge and collide with the pier of the bridge as result of the technical (most often the helm) damage.
3. Ships underway on the planned route in the area of the bridge which collide with piers as result of the of anti-collision manoeuvres.
4. Ships underway in area of the bridge which collide with the pier of the bridge as result of the missing to perform course change.
5. Ships which lost propulsion in the region of the bridge and are drifted towards the bridge pier.
6. Ships in the way which strikes bridge span as result of the too small clearance, what is most often due to the error of the navigator.

7. Ships under way which passes under movable bridge as the result of damages of the opening mechanism or the human error collide with the span of the bridge or it drops during closing on the ship's superstructure.
8. Ships which do not follow with recommended routes, in this fishing vessels and pleasure crafts.
9. Ships underway with her own established route under the bridge which crashes with the stern part with the pier as result of the influence of the current or the wind on the ship.

The logical tree of possibly scenarios of events and their results for above-categories is presented in *Figure 4*.

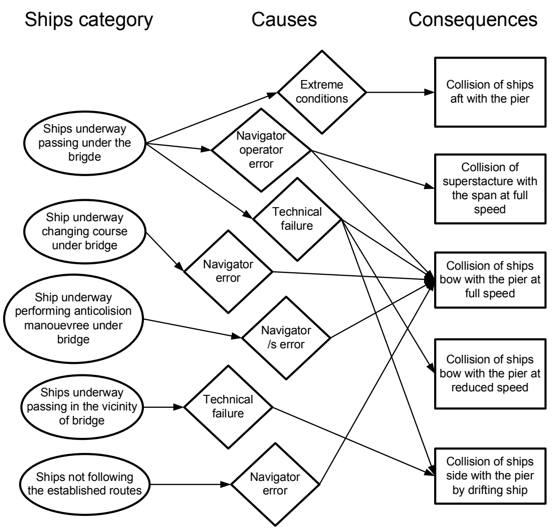

Figure 4. The logical tree of most possibly scenarios of ships collisions with bridges together with its reasons and results

The procedure of the risk management is the multistage rational method, targeting increasing of the safety of the shipping throughout the protection of lives and health's of people, environments and properties [2]. The procedure consists of the risk analysis (estimation), the assessment of the risk which requires of the decision about his acceptability and his temporary inspection. It consists of four following stages:

1. The identification of hazards.
2. Risk analyses (the estimation of the risk on the basis of data possessed without taking into account of changes in analysed area) which consists of assessing of the probabilities of the threats (probability assessment) and the qualification of consequences (consequence analysis).
3. Evaluation of the risks (the comparison of the risk with criteria values, to meet the acceptable level).
4. Risk managements (with the regard of methods of the risk reduction and its temporal control).

It is the risk analysis of ship-bridge collisions the measures of the societal risk described by FN (frequency – number) are widely used (*Figure 5*).

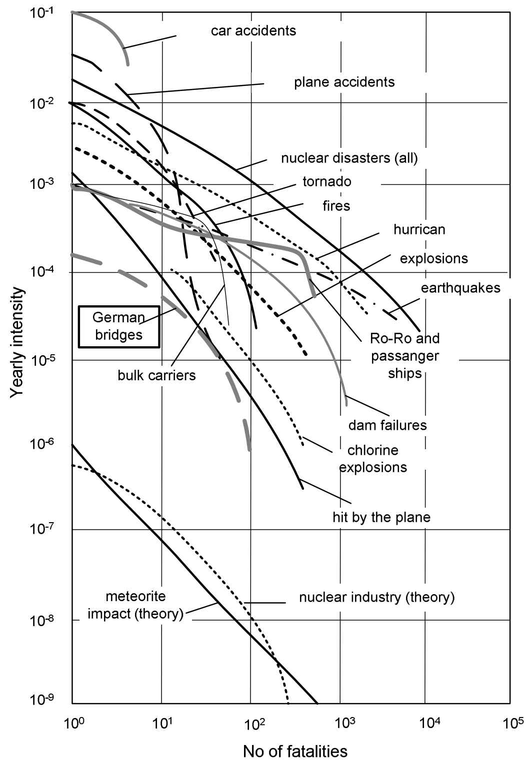

Figure 5. Example FN curves for different activities together with FN estimated for German historical bridges [3]

3. Acceptable levels of bridge collapse as result of the ships collision – comparison of criteria values

Acceptability criteria of break of the bridge connection risk is set up due to following factors:

- possible number of fatalities in the case of the traffic on the bridge,
- the degree of the importance of the bridge for the society or/and defence of the country,
- costs of the restoration and costs of the operation as result of the break of the bridge passage, qualified most often by means of CBA analyses.

Taking into account international and local regulations, the acceptability of the risk of the critical bridge by trespassing ships are varied in different designs of the bridge in the world. When risk acceptability criteria does not exists it is necessary to perform wide relations to the existing projects or to natural threats in the investigated region.

The probability applied for bridge failure in codes and international standards differs from 0,0001 to 0,001 for 100 year (10^{-6} to 10^{-5} per year). Analysing the accessible literature shown in [3] within the range of the risk acceptability of the bridge destruction as result of the collision with ship, following conclusions could be drawn:

1. For the project of the bridge through Great Belt the criterion of the bridge serious collision with ship was 1 per 10 000 years, that gives the probability of the bridge collapse 0,02 on 100 years (2.0 10^{-4} per year).
2. Given in 1985 the recommendation of the Louisiana State divide bridges on 2 categories. For deep water bridges (ships up to 13 m of the draught) the admissible probability of the destruction of the bridge as result of the ship is 0,01 on 100 years (10^{-4} a year).
3. The ISO standard puts limit probabilities of the destruction of the bridge as result of the collision with ship on level of 0,01 per 50 years, what gives value of 0,02 per 100 years (2,0 10^{-4} a year).
4. J.B. Menzies proposes to apply the acceptable risk of bridges destruction on level 2.0 10^{-6} which then the value seems to be nearing to norms quoted in Eurocode 1 EN1990:2002. It is worth of notice that this author ascertains, that in the past above the half of all destructions of bridges was due to event relied with the ship collision or the erosion the bottom at the pier as result of the flood.
5. Recommendations of the American Association of State Highway and Transportation Officials (AASHTO) assumes the probabilities of the bridge destructions on level from 0,1 and 0,01 per 100 years (10^{-3} and 10^{-4} a year) consecutively for standard- and critical bridges.
6. According to L. J. Vincentsena and S. Spangenberga in changed project of the bridge and the tunnel through Great Belt the accepted levels of the bridge road- and of railway link break simultaneously is set to 0,02 on 100 years, and bridge or railway alternatively as 0,1 on 100 years.
7. According to the report 63 of Construction Industry Research and Information Association the risk of the destruction of the construction can be definite as $P_z = (10^{-4}/n_r)K_s n_d$,, where P_z is a probability of the destruction of the construction due to any reason within a period of its operation n_d, n_r is a number of persons threatened in the accident and K_s is the coefficient dependent of values related with class of the building: places of public meetings, dams – 0,005; the household activity , the office, the trade or the industry – 0,05; bridges – 0,5; towers, masts and sea-constructions – 5. This criterion has became put-upon to the designing of the second bridge trough Severn river and brought the acceptability level to value of less than 4,0 10^{-7} per a year.
8. *Nordic Committee for Safety of Structures* gives legitimate values of the probability of the one year's damage as 10^{-3} to 10^{-7} for serious results or very serious.
9. JCSS gives criteria values on level 10^{-3} to 10^{-6} for damages with serious results.
10. AASHTO use the so called return periods. For the erosion the bottom at the pier as result of the flood it apply 100 and 500 years return-period adequately for regular and critical bridges (0,01 and 0,02 in the year), for earthquakes 475- and 2500-the years return-period (0,02 and 0,004) period and for the collision with ships 1000- and 10 000-years (0,001 and 0,0001 in the year).

One ought to notice that criteria of the risk acceptance in Europe are created usually for ccumulative all possibly events such as: seismic, fires, the bottom erosion at piers and the influence of ice etc. American criteria are built rather for single events. The above-analysis shows that the lack is generally accepted acceptability criteria of the risk. Guidelines have a considerable spread of the criteria values. The probability of the break of the bridge connection varies widely from 10^{-3} to 10^{-6}, can be accepted as the enter average value to further analyses.

4. Chosen case studies of the safety analysis with accident probability estimation of the ships passage under the bridges

Two example analyses concerning the quantifying of the risk of the ship passages under bridges thet restricts water area both concerning the horizontal and vertical area.

4.1. The collision with the span. Qualifying of horizontal clearance with the methods of the statistical simulation

The Monte Carlo based model was built of the clearance between ships and the span. The random variables and their parameters were estimated he the base results obtained in the project: "The creation of the method of dynamic and probabilistic underkeel clearance estimation". To build example solution the example bridge on the fairway Szczecin-Świnoujście with the height above water level of H = 36 m have been chosen. The maximum ship, which can enter to Szczecin now is ship with following parameters: L = 160 m, T = 9,15 m, and A = 35 m. The horizontal clearance has been calculated for two ship speeds 8 and 4 kn. Input data to the model one are presented in *Table 1*. Monte Carlo simulations were executed by means of the @Risk software, the number of samples equals 100 000, what gave the suitable statistical convergence of obtained results. The best fit of the clearance of the height to the span of the bridge gives the log-normal distribution with relatively low asymmetry. In further step it is possible to qualify the probability of the collision of the ship into the span of the bridge. From graphs presented in *Figure 6* it is apparently visible that 5% ships will keep a smaller than: 1,24 m and 0,86 m for investigated speeds 4 and 2 m/s It was confirmed also the argument about the relationship of the reserve of the height over by ship to the span with her speed, what results from the squat phenomenon.

Table 1. The random distributions of variables accepted to the Monte Carlo simulation of horizontal clearance to the bridge and their parameters

Variable	The symbol	The accepted average value	Distribution of errors	Parameters of given distribution
Bridge height [m]	*H*	36	uniform	(0; –0,05)
Draught [m]	*T*	9,15	normal cut	(0; 0,1; 0,2)
Ships air draught [m]	*A*	35	based on *T*	a.a.
Squat [m]	*O*	4 models	*bootstrap*	
Water level [m]	p_{wa}	0	normal cut	(0; 0,1, 0,15)
Breadth [m]	*B*	35	uniform	(35; 40)
Speed of the ship [in]	*v*	8 and 4	normal	(0, 0,5)

4.2. The collision with pier. The bridge Great Belt – the traffic analysis of ships by means of AIS

The AIS system could be a very useful tool to the traffic analysis of ships and their safeties also in the bridges area. It should be noted that the possibility exists of the GPS satellites signal reception difficulties and consecutive loss of ships position during the passage under bridge due to its shadowing effect. The traffic analyses of ships during the passage under the greatest European bridge Great Belt Western is presented. The traffic under the bridge is two-way. As an input data unprocessed signal from the AIS Baltic countries exchange network (AIS HELCOM) was applied. The number of registered passages was about 6500 ships per year in one direction. Research embraced the year 2011. Registered chosen passages of ships are showed in *Figure 7*. It is visible that some ships passed vary close to the pier of the bridge.

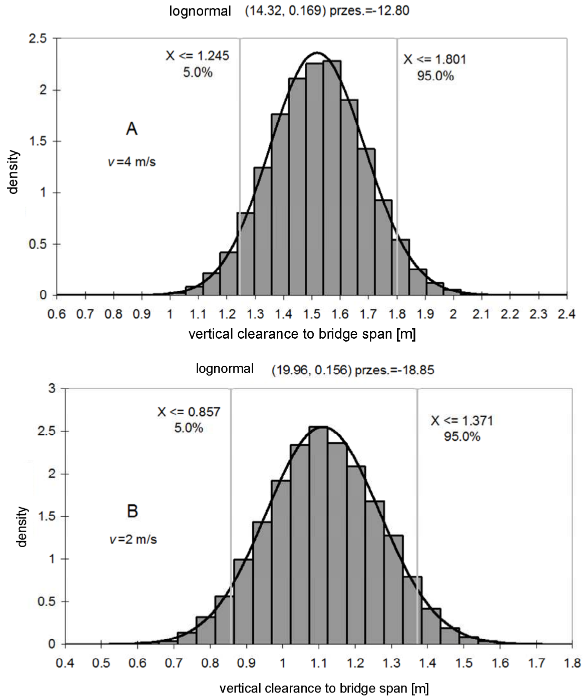

Figure 6. The distribution of the vertical clearance of the height over the ship to the span for two speeds of ships: A – 8 kn (abt. 4m/s) and B – 4 kn (abt. 2m/s)

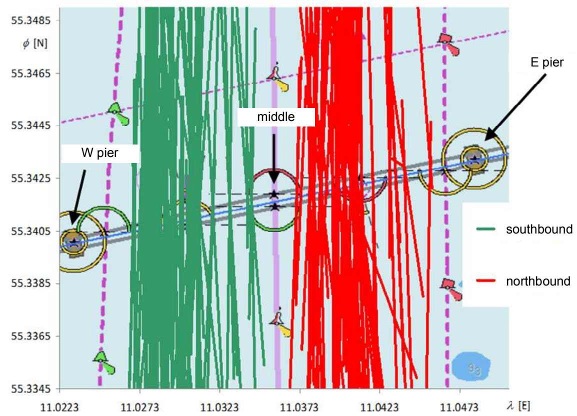

Figure 7. Registered routes of ships in the region of the Bridge Great Belt Eastern

In the next step the distributions of density probability of the position of registered positions of ships during the passage under the bridge have been analysed. The CDF of ships positions moving north is presented in *Figure 8*. The logistic distribution with parameters of a= 11,03 and b = 8,32 showed good fit to given empirical (the Kolmogorov–Smirnov tests was applied). It is visible that the probability of the collision with the western pier of the bridge lead to values of $6 \cdot 10^{-4}$, so shows the large agreement with the values meet in the literature. The probability of the exit outside the given route and intrusion to opposite traffic lane is higher and quails: $6{,}4 \cdot 10^{-3}$.

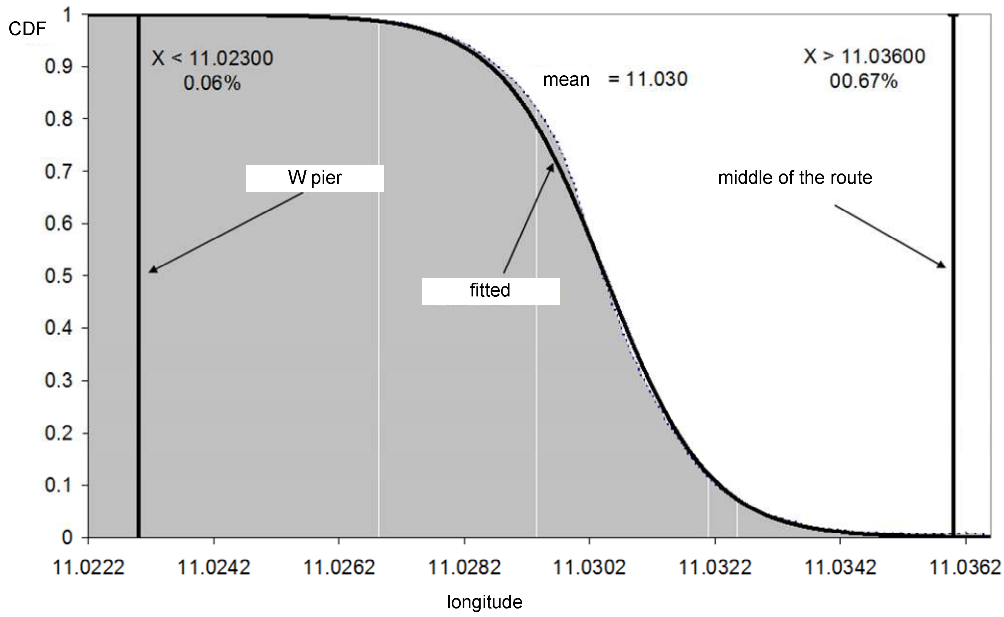

Figure 8. Cumulative distribution function of positions of ships under the bridge (the western route)

5. Conclusion

It was shown that the problem of collisions of ships with bridges in Poland and in around the world is serious, also on inland waterways. Additionally the fact of the considerable degradation of the infrastructure contributes to his deepening. There exists the row of methods of the valuation of the risk from which two were described.

The designing of new locations of bridges should be supported by individual risk analyses, because as it was showed norms and guidelines are sometimes inconsistent and not always assure optimum-foundations to their designing.

It is necessary to carry out of the deeper discussion in the matter of the safety of the location of bridges in the respect of collisions with ships in Poland especially that possible disasters can entail deadly sacrifices.

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