NAUTICAL RISK ANALYSIS FOR VIDIN-CALAFAT BRIDGE IN THE DANUBE

by

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ABSTRACT

At the request of FCC Construccion, S.A. in connection with the Danube Bridge project between Vidin (Bulgaria) and Calafat (Romania), a Nautical Risk Analysis was developed to assess the probability of impact of vessels on the unprotected piles of the bridge located in the secondary channel of the river. The project consists of a combination viaduct - cable-stayed bridge taking advantage of the small island in the middle of the channel. In each of the piles of the main channel a circular fender is arranged. Piles in the secondary channel are not protected.

The objective of the study was to evaluate eventual risk of impact on unprotected piles, assessing the probability of occurrence and making a proposal for preventive or corrective measures. Complete traffic statistics were available, as well as information on the river flow, current velocities and wind, from which the actual navigation conditions in this section of the river were modeled.

The study analyzed the consequences of exceptional situations (breakdowns in propulsion or steering of vessels, lack of visibility, errors in position estimation, sudden bad weather, etc.), beyond the normal difficulties in sailing the river.

The analysis **identifies, analyzes and evaluates** different **expected risk situations** in the development of manoeuvres in order to establish effective preventive or corrective measures in accordance with the most stringent recommendations. Applying a ship manoeuvrability numerical model, the response of the vessels to each of the measures was analyzed according to the different possible situations.

Consequently, it was possible to evaluate the effectiveness of these countermeasures by determining, where appropriate, the "point of no return", which serves as a basis for the definition of restricted areas and development of contingency plans. During the development of the work a program of emergency simulations was established using model SHIPMA (Delft Hydraulics and MARIN (The Netherlands)). This model reproduces the behavior of a specific vessel during the execution of port access or exit maneuvers, subjected to the action of environmental agents (wind, current, waves, limited depth, shore suction, etc.) and aided by tugs, if any. For this purpose, it has an autopilot and tug control, which develop the necessary actions to maintain a desired track.

The working procedure was developed in the following phases:

- Identification of risk events
- Assessment of response manoeuvres
- Accidental risk assessment
- Definition of preventive and corrective measures

Bridges are outstanding structures in inland navigation. They are usually located and designed (including the fendering system) based on deterministic guidelines and standardized codes. Sometimes, the relevance of the bridge requires more detailed analysis in order to better identify operation conditions and optimize the structural design and the fendering system, taking into account risk of impact by vessels. This is especially important in areas with high density of traffic. Risk analysis is not the standard approach, but this paper shows an interesting case where it provided very useful information for design and permitted significant savings.

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1. INTRODUCTION

In response to the request from FCC Construcción, S.A. a Nautical Risk Analysis Study was developed in relation to the Danube Bridge Vidin-Calafat connecting Bulgaria and Romania. The aim of the study was to evaluate the risk of collision of vessels and barges with the bridge piles, pile caps and piers (hereinafter referred to as piers) located in the secondary branch of the river, such that an appropriate impact loading could be determined for use in the design of the vessel impact protection system for the piers in the non-navigation spans.

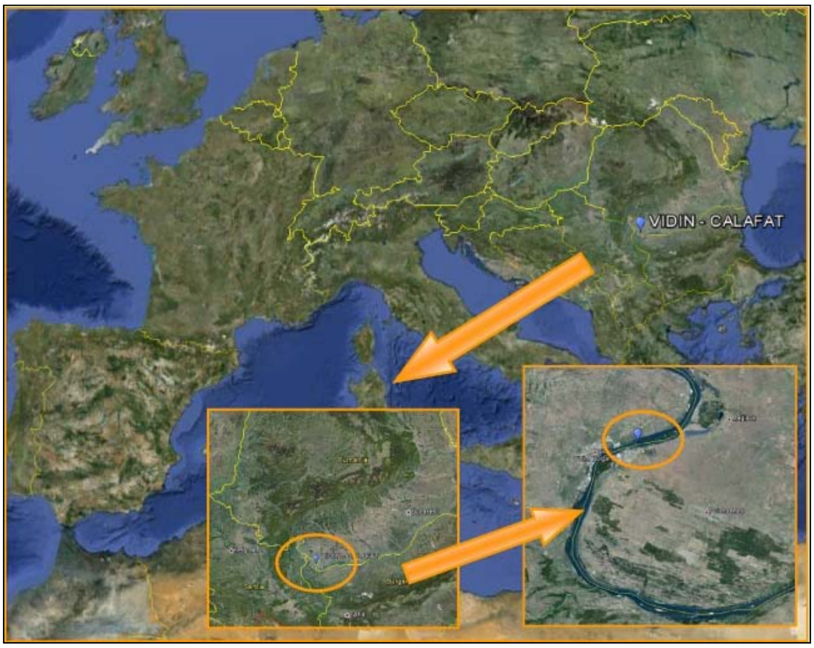

Figure 1: Bridge location

The bridge project consists of a combination viaduct plus tightened bridge taking advantage of the small island in the centre of the river. The piers of the bridge in the main river branch are protected against ship collisions by means of circular fender structures. The protection system for the piers of the viaduct in the secondary branch of the river was not developed at the time of the analysis.

Therefore, eventual risk scenarios related to vessel collisions with the viaduct piers should be evaluated. The probability of occurrence of such incidences was estimated and preventive or corrective measures were defined accordingly. An evaluation and justification of any potential for reducing the impact protection forces to be applied to the fixed structures (the piers) was undertaken.

The objective of the study was therefore the identification, analysis and evaluation of different risk hypotheses which could be expected during the development of the river transit. As a result, preventive or corrective actions and measures were defined and tested. As a reference, AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges (second edition 2009) and IMO (International Maritime Organization) recommendations were considered regarding risk situations. The study also took account of the reference included in the prEN 1991-1-7 Eurocode 1 - Actions on structures.

Two methods were applied in this study to determine the risk related to vessel collisions with the viaduct piers located in the secondary branch of the river:

- First method is a detailed risk analysis procedure for estimating the risk based on AASHTO Guide Specification.
- Second method is a cost-effectiveness analysis procedure for estimating the risk based on a simulation program covering emergency situations. A numerical model (SHIPMA) was used for the analysis.

The first method provides that the vessel collision requirements are aimed at preventing a vessel from impacting a bridge over a navigable waterway and causing excessive damage. A probabilistic model based on a worst-case-scenario, where a fully loaded fast moving vessel collides with a pier while moving unimpeded, is used to determine whether a bridge is adequately designed. In determining the feasibility of a given bridge it is necessary to consider the waterway geometry, the types of vessels using the waterway, the speed and load condition of the waterway vessels, and the response of the structure in the event of a vessel collision. If a structure is unable to resist the vessel collision forces, it needs to be protected by a fender system.

The second method is a cost-effectiveness analysis procedure for determining the risk level on a set of scenarios in which specific error situations or conditions are assumed to occur or exist on a ship prior to or during passage of the bridge. A simulation program covering emergency situations was defined and a numerical model was used for the analysis. This was SHIPMA, a fast-time manoeuvring model developed by Delft Hydraulics and MARIN (The Netherlands). This model computes the track and course angle of a vessel, taking into account the influence of wind, waves, currents, current gradient, variable water depth and bank suction. SHIPMA is a "fast-time" autopilot manoeuvring model, different from a real-time bridge simulator. Rudder, engine, bow thruster and tug control is done by a track-keeping autopilot that anticipates deviations from the desired track. A probabilistic model was also applied to obtain the annual frequency of collapse similar to that of the first method.

Figure 2: Bridge project Vidin-Calafat

The acceptable probability for any given bridge depends on the importance that the bridge serves to the community. Bridges may be categorized as either “critical” or “regular” according to AASHTO LRFD code Section 3.14.3. If a bridge is classified as critical, it must remain operational after a vessel collision. Once a bridge’s classification has been established, it is determined to have met the criteria according to its completed annual frequency of collapse.

The correct development of the risk analysis makes it necessary to manage detailed river traffic statistics (number and type/size of vessels upstream-downstream). A fluvial regime (distribution of water levels and corresponding current speeds) should be described as well, together with wind distribution (wind directions and speed). Based on the information available, different ship transit scenarios were defined in accordance with the existing conditions for navigation in this river section.

2. DATA COLLECTION

The first step in the vulnerability (risk) assessment process was to collect data concerning the waterway characteristics, the vessel fleet using the waterway, and the characteristics of the bridge.

The Danube Bridge Vidin - Calafat is located at km 796 of the Danube River crossing from the northern Bulgarian side to the southern Romanian side, which is due to a river bend that inverts the generally opposite location of the two countries. The Danube is the only major European river draining into south eastern direction into the Black Sea and with 2880 km length its second longest.

In the bridge location area the navigation route permits a 4400 m straight waterway. Under the bridge, the navigation width is narrowed to 150 m after reduction of the pier area. In the upstream and downstream part the route adapts from the wider bridge channel to the 200 metres total width of the navigation channel after 600 metres transition length.

Hydraulic characteristics were described by means of velocity distribution at the cross-sections for different elevations of the water surface. The vessel collision analysis was based on a water level of 32.0 meters and mean speed of the current of 1.2 m/s.

Climate conditions were analyzed by considering distribution of wind velocity from different directions for Vidin area. W sector collects wind data from SW, W and NW directions and E sector collects wind data from NE. E and SE are the most important sectors with a frequency of occurrence around 57.5% (210 days/year) and 31.7% (116 days/year), respectively.

Information about the number of vessel trips was obtained from ships that passed Iron Gates II lock located in Turnu Severing (Romania). This information was supplied by FCC Construcción, S.A. Manual analysis was executed to extract general vessel data and tonnage for the actual vessels transiting the waterway at the location of the bridge Vidin-Calafat. Additional information about the sizes and types of vessels was used from CEMT Class (European Conference of Ministers of Transport) classification.

The total number of estimated transits for the existing vessel design fleet is 4577 trips per year (about 13 trips per day). This total fleet consists of 1782 pusher convoys transits, 2033 self-propelled barge convoys and 371 passenger ships. Convoys are the predominant category of vessels navigating the Danube in this area.

PB1 to PB8 piers were considered for an impact of a vessel at level 36.0 m. The values of Ultimate Load State (ULS) or ultimate bridge resistance used for vessel impact analysis were calculated by FCC Construccion S.A. These values were used to calculate the probability of bridge collapse, computed according to the ratio of ultimate bridge resistance (ULS) to the vessel impact force.

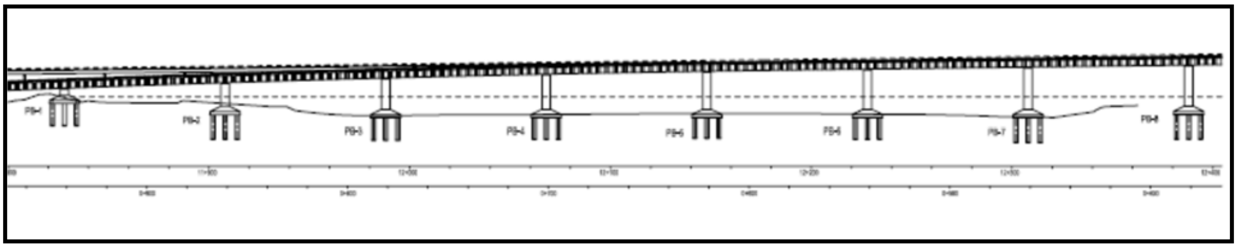

Figure 3: PB1 to PB8 piers

The data collection process is usually the most time-consuming part of the risk analysis. It has to be conducted in a thorough manner since the input values determined from the data collection will be used for the risk assessment. If the input data is incomplete or incorrect, the risk evaluation will be flawed and could result in incorrect conclusions. The data collected will come from a variety of disparate sources and it must be assessed and organized into a meaningful, coherent representation of the waterway, vessel fleet, and bridge characteristics.

3. AASHTO GUIDE SPECIFICATIONS. RISK ASSESSMENT

3.1. Introduction

This section describes the method to determine the risk related to vessel collisions with the viaduct piers located in the secondary branch of the river. It is a detailed analysis procedure for estimating the risk based on AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges.

In navigable waterway areas, where vessel collision by merchant ships and barges may be anticipated, bridge structures shall be designed to prevent collapse of the superstructure by considering the size and type of the vessel, available water depth, vessel speed and structure response. The AASHTO requirements apply to all bridge types which cross a navigable shallow draft inland waterway or canal with barge traffic, and deep draft waterways with large merchant ships.

The intent of the vessel collision AASHTO requirements is to establish analysis and design provisions to minimize bridge susceptibility to catastrophic collapse. The purpose of the provisions is to provide predictable design vessel collision effects in order to provide bridge components with a reasonable resistance to collapse.

Vidin-Calafat Bridge is over a navigable waterway meeting the criteria above. Therefore, it was evaluated as to vulnerability to vessel collision in order to determine prudent protective measures.

The AASHTO Guide Specifications contain three alternative analysis methods for determining the design vessel for each bridge component in the structure in accordance with two-tiered risk acceptance criteria:

- Method I is a simple to use semi-deterministic procedure
- Method II is a detailed risk analysis procedure
- Method III is a cost-effectiveness analysis of risk reduction procedure (based on a classical benefit/cost analysis)

The Guide Specifications require the use of Method II risk analysis for all bridges unless special circumstances exist as described in the code for the use of Method I and III. Special circumstances for using Method I include shallow draft waterways where the marine traffic consists almost exclusively of barges. Method III application includes very wide waterways with many piers exposed to collision, as well as existing bridges to be retrofitted.

Method II of the AASHTO Guide Specifications was applied. It is a probability-based risk analysis procedure for determining the appropriate vessel impact design loads for a bridge structure. Using Method II procedures, a mathematical risk model is used to estimate the annual frequency of bridge collapse based on the bridge pier/span geometry, ultimate resistance of the pier (or span), waterway characteristics, and the characteristics of the vessel fleet transiting the channel. The estimated risk of collapse is compared to standard acceptance criteria, and the bridge characteristics (span layout, pier strength, etc.) are adjusted until the acceptance criteria are satisfied. For example, if a structure is unable to resist the vessel collision forces, it needs to be protected with a fender system.

The acceptable probability for any given bridge depends on the importance that the bridge serves to the community. Bridges may be categorized as either “critical” (essential bridges) or “regular” (typical bridges) according to AASHTO Guide Specifications. If a bridge is classified as critical, it must remain operational after a vessel collision. Once a bridge’s classification has been established, it is determined to have met the criteria according to its completed annual frequency of collapse.

Vidin-Calafat bridge is classified as “critical”: the social/survival evaluation is largely concerned with the need for roadways connecting the communities located on opposite sides of the waterway.

Critical bridges is a situation where Method I should not generally be used. So Method II of the AASHTO Guide Specifications was applied.

The AASHTO Guide Specifications code uses annual frequency of collapse to determine whether a bridge design is satisfactory. An alternative way of representing a bridge’s vulnerability is with the inverse of annual frequency of collapse, or return period. A bridge’s return period is the number of years on average that a bridge may be expected to stand before a vessel collides with it and causes it to collapse. The annual frequency of collapse resulting from collision of a single pier by a vessel is calculated as follows:

$$AF_{ij} = (N_i)(PA_{ij})(PG_{ij})(PC_{ij})$$

where:

AFij = Annual frequency of collapse of pier j caused by vessel type i

Ni = Annual number of vessel type i (a vessel must pass all piers)

PAij = Probability of aberrancy of vessel type i with respect to pier j

PGij = Geometric probability associated with vessel type i and pier j

PCij = Probability of collapse of pier j due to vessel type i

The equation suggests that the annual frequency of collapse is based on a number of different probabilities. In sequence we need to know the probability that a vessel becomes aberrant; then, the probability that a vessel will strike the bridge given that it becomes aberrant; and finally, the probability that the bridge will collapse given that a vessel is aberrant and strikes the bridge.

The overall annual frequency of collapse of a bridge, AFTotal, is the sum of the annual frequencies that result from collisions of the various vessel types with the various bridge piers that one deemed vulnerable due to their location relative to the channel. Thus, we have:

$$AF_{Total} = \sum_{i=1}^{NV} \sum_{j=1}^{NP} AF_{ij}$$

where:

AFTotal = Annual frequency of collapse of the bridge

NV = Number of vessel types (i.e., including the same loading condition, size, etc.) that pass the bridge

NP = Number of bridge piers within three times the overall length (LOA) of the vessel from the navigable channel centreline

The sequence of computations is such that the annual frequency of collapse is determined for each pier and the sum of these frequencies for all piers provides the overall annual frequency of collapse of the bridge. For a bridge classified as “critical,” the annual frequency of collapse must not be higher than 0.0001, which means that its return period must not be shorter than 10000 years. The required annual frequency of collapse for a bridge designated as “regular” must be no larger than 0.001 corresponding to a return period of 1000 years. In terms of these acceptable levels, we have:

$$AF_{Total} < AF_{Acp}$$

where:

AFTotal = Annual frequency of collapse of the bridge

AFAcp = Acceptable annual frequency of collapse of the bridge

3.2. Acceptance Criteria

Risk can be defined as the potential realization of unwanted consequences of an event. Both a probability of occurrence of an event and the magnitude of its consequences are involved. Risk estimation is the process used for controlling such risk and arriving at an acceptable level of risk.

There are many approaches to evaluating risks in order to determine acceptability. The most important of these can be grouped into two broad categories:

- risk comparison approaches
- cost-effectiveness of risk reduction

In this study, risk comparison was used to establish the Method II acceptance criteria. The AASHTO Guide Specifications established an acceptance criterion of frequency of collapse, AF, for bridge collapse associated with vessel collision:

AF < 0.0001 per year for critical/essential bridges

AF < 0.001 per year for typical bridges

The acceptable annual frequency of bridge collapse for the total bridge as determined above shall be distributed over the number of pier and span elements located within the waterway, or within the distance 3 x LOA on each side of the inbound and outbound vessel transit paths if the waterway is wide. This results in an acceptable risk criterion for each pier and span element of the total bridge.

Vidin-Calafat bridge is classified as “critical”, as the social/survival evaluation is largely concerned with the need for roadways connecting the communities located on opposite sides of the waterway, so it should comply with the criterion AF < 0.0001 per year.

3.3. Probability of Aberrancy (PA)

The probability of aberrancy is the likelihood that a vessel deviates off course due to pilot error, poor weather conditions or mechanical failure. One of the three main components to determine the annual frequency of bridge collapse, the probability of aberrancy can be calculated by two different methods. The first method involves performing a statistical analysis of historical data from a given channel. While this method is the most accurate, it can be time consuming and difficult. The simplified approach detailed in AASHTO LRFD 3.14.5.2.3 is an approximation method and can be written:

$$PA = (BR)(R_B)(R_C)(R_{XC})(R_D)$$

where:

PA = Probability of aberrancy

BR = Aberrancy base rate

RB = Correction factor for bridge location

RC = Correction factor for current acting parallel to vessel transit path

RXC = Correction factor for cross-current acting perpendicular to vessel transit path

RD = Correction factor for vessel traffic density

3.4. Geometric Probability (PG)

Once a vessel has become aberrant, it is then necessary to estimate the probability that the vessel will strike the bridge. To do this, geometric considerations are necessary. The geometric probability is based on a number of parameters including the geometry of the waterway, water depth, location of bridge piers, span clearance, sailing path of vessel, manoeuvring characteristics of the vessel, location, heading and velocity of vessel, rudder angle at time of failure, environmental conditions, width, length and shape of vessel, and vessel draft.

3.5. Probability of Collapse (PC)

Given that a vessel has gone aberrant and has struck a pier, it is then necessary to estimate the probability that the bridge will collapse. Several variables including vessel size, type, configuration, speed, direction of impact and mass influence the probability of collapse. The stiffness of the bridge piers and the nature of bridge superstructure also influence the probability of bridge collapse. The AASHTO LRFD code Section 3.14.5.4 which addresses probability of collapse was developed by Cowiconsult (1987) based on studies performed by Fujii and Shiobara (1978) using Japanese historical damage data on vessels colliding at sea (AASHTO LRFD C3.14.5.4). The ratio of ultimate lateral resistance to the vessel impact force is computed in order to estimate the probability of collapse.

3.6. Risk analysis

Based on the risk analysis results for the non-navigation piers of Vidin-Calafat Bridge, 8 piers were exposed to potential collision (although piers PB-1 and PB-2 would be exposed only if very high water levels occurred).

The annual frequency of bridge collapse estimated was AF = 0.0000225 (a corresponding return period of 1 collapse in 44389 years).

The acceptance criteria for a critical/essential bridge classification is an annual frequency of bridge collapse equal to, or less than, AF = 0.0001 (a return period of 1 in 10000 years).

Therefore, the annual frequency of bridge collapse was lower than the acceptance criteria for a critical/essential bridge, so regarding the protection system for the piers of the viaduct in the secondary branch of the river, PB1 to PB8 located in the non-navigation zone, they did not require to be protected against ship collisions.

3.7. Sensitivity Analysis

A sensitivity analysis was executed for the most influential parameters in the risk assessment developed in previous sections:

- Vmax - design impact speed
- Vmin - minimum design impact speed
- Displacement - Length
- Aberrancy Base Rate
- Increase in number of Vessel Trips

In all cases analyzed the value of the annual frequency of collapse was lower than the acceptance criteria. High values of Vmax -design impact speed- ≥5.6 m/s for downbound transit and ≥4.2 m/s for upbound transit resulted in corresponding values of annual frequency of collapse 0.000114 > 0.0001 (acceptance criteria). These values of navigation speed are not permitted in the area, because the ferry service Vidin-Calafat requires the ships to reduce speed and increase the vigilance.

4. SHIP NAVIGATION NUMERICAL MODEL (SHIPMA). RISK ASSESSMENT

4.1. Introduction

This section describes the second method to determine the risk related to vessel collisions with the viaduct piers located in the secondary branch of the river. It is a cost-effectiveness analysis procedure to determine the risk level on a set of scenarios in which specific error situations or conditions are assumed to occur or exist on a ship prior to or during passage of the bridge.

A simulation program covering emergency situations was defined and a ship manoeuvring numerical model was used for the analysis. This is SHIPMA, a fast-time manoeuvring model developed by Delft Hydraulics and MARIN (The Netherlands). This model computes the track and course angle of a vessel, taking into account the influence of wind, waves, currents, current gradient, variable water depth and bank suction. SHIPMA is a "fast-time" autopilot manoeuvring model, different from a real-time bridge simulator. Rudder, engine, bow thruster and tug control is done by a track-keeping autopilot that anticipates deviations from the desired track. A probabilistic model was applied to estimate the annual frequency of collapse comparable to the first method.

4.2. Description of SHIPMA model

The study was developed applying the fast-time ship manoeuvring model SHIPMA, developed by Delft Hydraulics-MARIN (The Netherlands). This program simulates the manoeuvring behaviour of a ship.

The mathematical model computes the track and course angle of the vessel, taking into account the influences of wind, waves, currents, shallow water and bank suction. Rudder, engine and tug control is effectuated by a track-keeping auto-pilot that anticipates deviations from desired track and changes in currents. Control algorithms are also available for bow and stern thrusters.

The application of SHIPMA is primarily in port and fairway design, referring to both approach channels and inland waterways. According to PIANC a first estimate of the required channel width based on their methodology has to be followed by ship manoeuvring simulations. The mathematical model is used in port design and inland waterway studies to give the designer an insight into the inherent possibilities and restrictions of vessels, infrastructure, and environmental conditions. Based on the insights gained, mitigation, if needed, of the infrastructure design (channel layout, manoeuvring basin and terminal layout) and/or the admittance policy can be proposed. In a more detailed design the SHIPMA study will usually be followed by a study with a real-time manoeuvring simulator.

The following flow diagram gives an overview of the program structure:

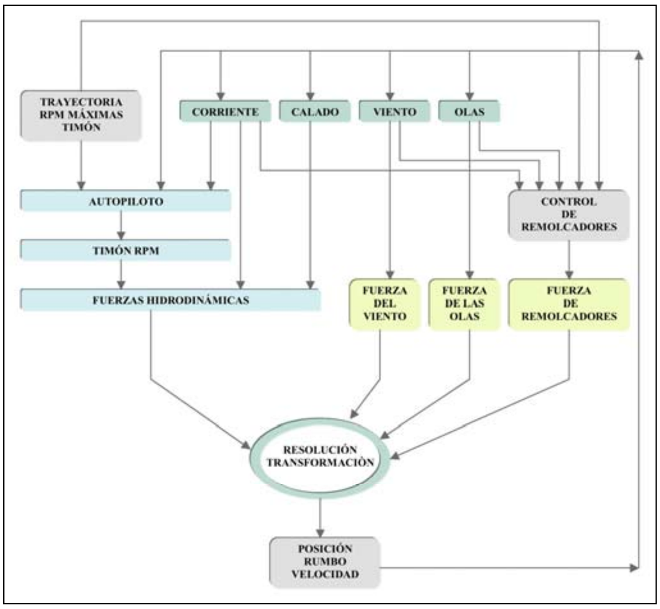

Figure 4: Flow diagram of SHIPMA model

4.3. Hazard Identification

All accident scenarios with significant contributions to the risk of collision are identified and analyzed in this phase. A very large fraction (about 80%) of navigational accidents are caused by human error or negligence, and detailed representation of human error is therefore necessary for the methodology to be successful.

An alternative approach in ship collision risk analysis is to base the risk of collisions on a set of scenarios in which specific error situations or conditions are assumed to occur or exist on a ship prior to or during passage of the bridge.

Emergency manoeuvres were simulated with the selected vessels using SHIPMA model in order to identify those cases in which the vessels drift towards the piers of the bridge when they are either sailing upstream or downstream in the Danube river.

The following emergency manoeuvres were considered:

- Loss of propulsion (black-out): at a specific point when passing near the bridge the engines fail and the vessel begins to drift under the influence of the prevailing conditions (wind and current).
- Extreme weather conditions (wind): in the vicinity of the bridge the wind suddenly increases. As a result, the vessel is sailing under extreme conditions.
- Escape manoeuvre: required following some type of error (poor visibility, incorrect positioning, etc.) which modifies the ship course towards the non-navigable branch of the river. The ship's rudder is then turned hard to avoid entering the risk area. This manoeuvre was carried out with the rudder hard to port and starboard.
- Crash-stop: required following some type of error (poor visibility, incorrect positioning, etc.) which modifies the ship course toward the non-navigable branch of the river. Eventually engines are put full astern to stop the ship and avoid entering the risk area.

This study only analyzed the engine shut down sailing the Danube because it was considered the main reason that could make the vessel drift toward the bridge piers. According to this, black-out manoeuvres were simulated.

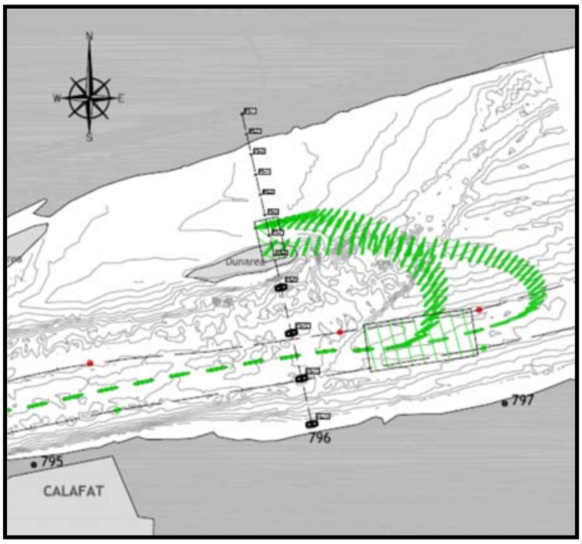

Figure 5: Black-out manoeuvres upstream

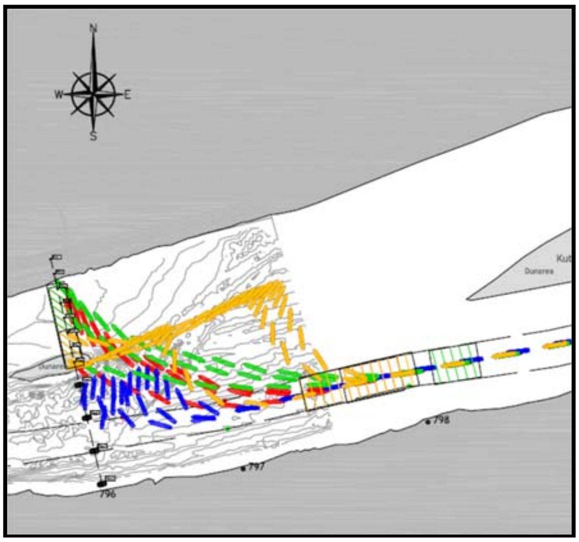

Figure 6: Black-out manoeuvres downstream

4.4. Description of the Vessels

Four inland waterway vessels typically used in the area were analyzed:

- Class IV (ES) (82.9x9.5x2.5 m. Displacement 1600t)
- Class Vb (SV) (187.0x11.4x2.8 m. Displacement 4924 t)
- Class VIb (SV) (185.0x22.8x3.0 m. Displacement 10102 t)
- Passenger Ship (130.0x22.0x1.7 m. Displacement 4000 t)

4.5. Assessment of Manoeuvres

For each vessel, possible collision incidents with the piers (PB-1 to PB-8) of the bridge in Danube river were analyzed due to loss of propulsion of the vessel.

The cases studied considered that the vessel sailed upstream or downstream affected by wind from different directions, under the effect of river flow. Three possible locations for loss of engine-power were used as benchmarks for each condition, so that a precaution area was established, associated with loss of propulsion or any other circumstance that caused the ship to drift toward the piers. Therefore, a sensitive navigation area was defined affecting bridge piers safety.

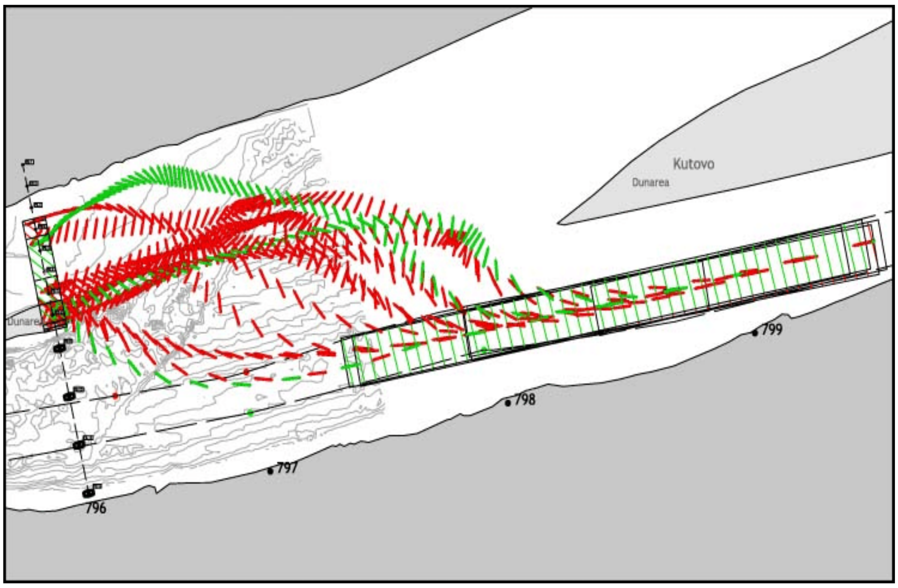

Figure 7: Black-out manoeuvres downstream and sensitive area

4.6. Frequency Analysis

The collision frequency analysis was carried out by identifying critical situations, denoted collision scenarios, where a ship-bridge collision could occur. A model was then developed for each scenario and an estimate of the frequency of collision as a result of the specific critical situation was computed. Information regarding waterway and bridge layout, weather conditions and ship traffic was used as input to the model to yield an estimate of the annual ship-bridge collision frequency.

The collision frequency computations took the following scenarios into account:

- “Powered Collisions”: collision occurs when a vessel is directly on collision course towards a pier and no evasive actions are carried out. This collision type is also referred to as a collision due to human error.
- Drifting ship collision can occur when a vessel suffers an engine failure and drifts towards a pier.

4.7. Powered collision

The powered collision occurs when a ship, due to human failure, continues its course along the shipping routes directly into a pier. There are two assumptions which have to be satisfied in order for a powered collision to occur:

The vessel has to be on collision course, i.e. the direction of travel is directly towards a pier. Such vessels will be referred to as a “collision candidates”

A collision candidate must hold its course and not perform any evasive actions.

- The probability of sustaining a collision course is denoted “the probability of human error”.
- The causes for human error can be the following:
    - Absence from bridge
    - Present but distracted
    - Present but incapacitated due to accident or illness
    - Present but asleep from fatigue
    - Present but incapacitated from alcohol
    - Ineffective radar use (bad visibility only)

The collision frequency for powered collisions on navigation path is calculated using the following equation:

$$F_C = \sum_{i=1}^{Ntr} N \cdot P_t(x) \cdot P_i(x) \cdot P_C \cdot P_{reac}(x)$$

where:

FC = Frequency of a passing vessel colliding under bridge (per year)

N = Total traffic on the type of vessel (vessels/year)

x = Position on the navigation path

Pt(x) = Probability of being on position x on the navigation path

Pi(x) = Poffset x Pcourse, probability of having a certain offset on the current x-position and probability of following a certain course heading towards the piers (course deviation)

PC = Probability of human failure or technical failure of navigational equipment, covering human error causes listed above

Preac(x) = Probability of the crew onboard being unable to react in time to correct the navigational error (depends on x)

4.8. Drifting ship collision

In case of failure in the propulsion engine the ship will start to drift, which will introduce a risk of collision if the drifting direction is towards the bridge pier. If a vessel is to collide with a pier, then the following conditions must be satisfied:

- The vessel has to be on collision course, i.e. the wind/current is moving the ship directly towards a pier. Such vessels will again be referred to as “collision candidates”
- A collision candidate must hold its course and not perform any evasive actions until the point of impact. The evasive actions considered are fixing the propulsion engine or successful anchoring.

For drifting collisions, a basic method is used to estimate the probability that ships experiencing a breakdown (i.e. loss of power, propulsion and/or steering) drift to a bridge pier. The model includes estimations of frequency of ship breakdown at specific locations and also of effectiveness of mechanisms that help take control of the vessel again. These mechanisms include emergency salvage, self repair, and anchoring.

The frequency of vessels drifting from a navigation path and colliding with an object near the lane can be written as:

$$F_{CD} = \sum_i N_i \bullet F_{drift} \bullet T_i \bullet P_{D1} \bullet P_{D2} \bullet P_{D3}$$

where

FCD = Collision frequency of drifting vessels (per year)

Ni = Number of vessels of ship type i in the area around the object (vessels/year)

Fdrift = Frequency of breakdown (per hour)

Ti = Average time a vessel of ship type i spends in the area to be considered for the calculation of the collision frequency (hours)

PD1 = Probability of the ship drifting towards the object

PD2 = Probability of not receiving any effective external help before a collision occurs

PD3 = Probability of no collision avoidance by the ship before a collision occurs (i.e. the crew is unable to stop the drifting through self-repair, anchoring, etc.)

If there are several navigation paths, the total collision frequency is the sum of the collision frequencies of each path.

4.9. Risk Analysis

In the previous section the expected frequency of ship collision with a pier in the bridge was estimated. In order to obtain the risk (frequency x consequences), the consequences must be determined.

In the event of a ship colliding with a pier, it could either lead to a severe damage of the bridge and/or the vessel. It may also be the case that the ship barely touches the bridge resulting in a less severe or insignificant damage.

In the following paragraphs, only consequences related to the collapse of the bridge are considered. Therefore, the probability of bridge collapse (PC) will be calculated due to a collision with an aberrant vessel (frequency of collision both powered and drifting, FC).

AF will be computed for each bridge pier and vessel classification:

$$AF = FC \times PC \quad = \text{risk}$$

The summation of all element AFs equals the annual frequency of collapse for the entire bridge.

Given that a vessel has gone aberrant and has struck a pier, it is then necessary to estimate the probability that the bridge will collapse. Several variables including vessel size, type, configuration, speed, direction of impact and mass influence the probability of collapse. The stiffness of the bridge pier and the nature of bridge superstructure also influence the probability of bridge collapse. The AASHTO LRFD code Section 3.14.5.4, which addresses probability of collapse was developed by Cowiconsult (1987) based on studies performed by Fujii and Shiobara (1978) using Japanese historical damage data on vessels colliding at sea (AASHTO LRFD C3.14.5.4). The ratio of ultimate lateral resistance to the vessel impact force is computed in order to estimate the probability of collapse (see section 3.4.3).

The following table summarizes the results obtained:

Table 1. Frequency of collision and annual frequency of collapse

Type of collision	Collision Frequency	Annual Freq. Collapse
Powered	1.41E-04	1.09E-05
Drifting	2.98E-03	3.85E-06
Total	**3.12E-03**	**1.48E-05**

5. CONCLUSIONS

The following table shows a comparison of the results obtained by the two methods applied:

Table 2. AASHTO Method and Numerical Model (SHIPMA). Summary of results

Method	Collision Frequency	Annual Freq. Collapse
AASHTO	1.17E-02	2.25E-05
NUMERIC MODEL	3.12E-03	1.48E-05
Method	**Collision Period**	**Collapse Period**
AASHTO	85	44389
NUMERIC MODEL	320	67796

Finally, the acceptance criteria recommended by AASHTO was applied (AF < 0.0001). For both methods, the annual frequencies of bridge collapse are lower than the acceptance criteria for a critical/essential bridge. Therefore, regarding the protection system for the piers of the viaduct in the secondary branch of the river, PB1 to PB8 located in the non-navigation zone, they do not require to be protected against ship collisions.

It is important to remember that the risk is a composite of two values: frequency of occurrence of a ship-bridge collision and its consequences. In this case, the expected frequencies of collision are 1 in 85 years according to AASHTO Method and 1 in 320 years according to Numerical Model (SHIPMA) results. These expected periods of collision could be interpreted in the sense that for a design life of 100 years, the probability of a ship-bridge collision is not negligible. However, the results of the computation of the annual frequency of collapse (return periods higher than 10000 years (acceptance criteria)) mean that if there would be a ship collision, the bridge piers will resist the impact and therefore the bridge will not collapse or the probability of collapse is extremely low.

The importance of the bridge pier impact resistance values should also be considered (PB-3 to PB-8) for the final result of the analysis using AASHTO methodology. According to this aspect, the value of the Ultimate Load State (ULS) for piers PB-3 to PB-8 used in calculations must be at least those considered in this study. So these values shall be the minimum protection required for the piers.

Bridges are outstanding structures in inland navigation. They are usually located and designed (including the fendering system) based on deterministic guidelines and standardized codes. Sometimes, the relevance of the bridge requires more detailed analysis in order to better identify operation conditions and optimize the structural design and the fendering system, taking into account risk of impact by vessels. This is especially important in areas with high density of traffic. Risk analysis is not the standard approach, but this paper shows an interesting case where it provided very useful information for design and permitted significant savings.

6. REFERENCES

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