Ship Impact Studies for the Forth Replacement Crossing

Matt CARTER
Associate Director
Arup
Hong Kong
matt.carter@arup.com

Steve KITE
Associate Director
Arup
London
steve.kite@arup.com

Naeem HUSSAIN
Director
Arup
Hong Kong
naeem.hussain@arup.com

Summary

The Forth Replacement Crossing (FRC) is a EUR 2.2 B project to construct a 2.6 km cable stayed bridge together with associated network connections. The Firth of Forth, which the bridge crosses, is a navigable waterway with tankers, ferries and container vessels up to 45,000 tonnes displacement passing under the bridge. Marine risk and ship impact loads are important design considerations.

A quantitative marine collision risk assessment and cost-benefit analysis was carried out in accordance with the As Low As Reasonably Practical (ALARP) principle to determine the required impact resistances of the piers. Unique aspects of the methodology were the development of a semi-holistic model for collision probability and an explicit function for probability of collapse.

Keywords: cable-stayed bridge; design; ship impact; Eurocode; risk assessment; ALARP.

1. Introduction

The Firth of Forth is a dramatic estuary which separates the Scottish capital of Edinburgh from the Kingdom of Fife to the north. A new bridge will be built slightly to the west of the two existing downstream crossings making use of Beamer Rock, a natural dolerite outcrop in the middle of the Forth, which allows the wide estuary to be crossed by a pair of 650 m cable stayed spans (Figure 1). The development of the unique design of the bridge has been described by Carter et al [1].

The bridge is being designed to the structural Eurocodes which have recently replaced British Standards as the basis of design for bridges and other structures in the UK.

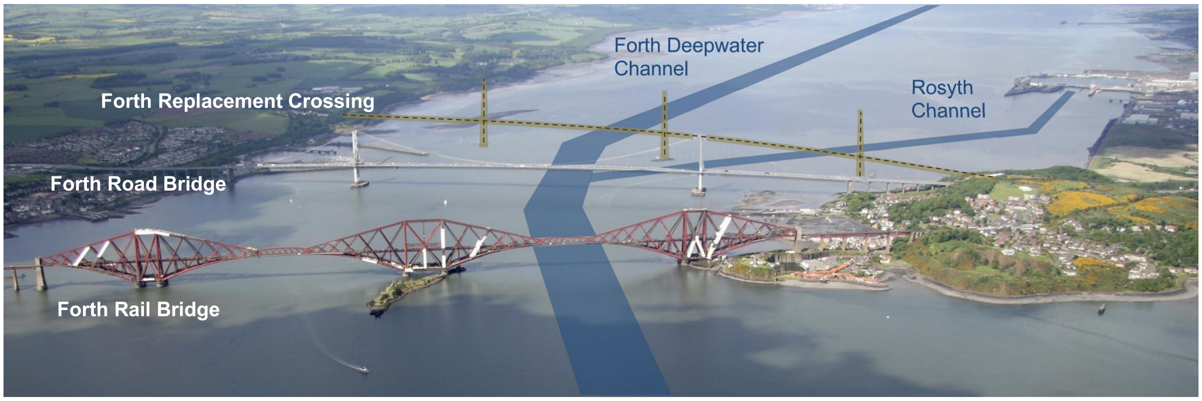

Fig. 1: Location of the Forth Replacement Crossing

The southern main span crosses the Forth Deepwater Channel (FDC), the main access to the upstream ports. Grangemouth is Scotland's main oil port and home to one of the biggest petrochemical plants in Europe. It is also a busy container port, handling trade with North America

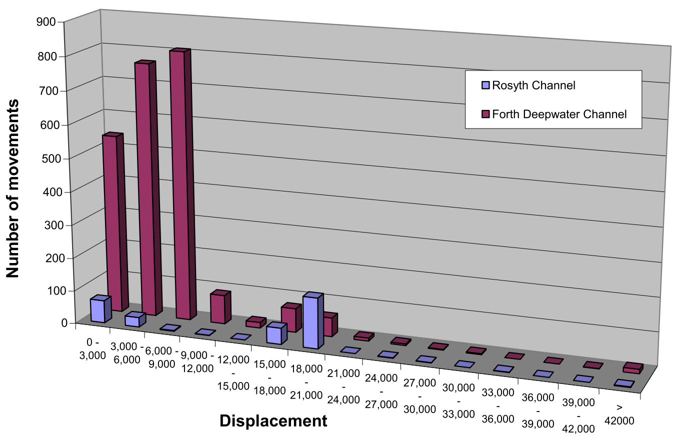

Fig. 2: Vessel Frequency Distribution

and Europe. Crombie provides munitions and maintenance support to military vessels and Royal Fleet Auxiliaries.

The northern main span crosses the approach into Rosyth port, which is the terminal for a ferry route to Zeebrugge as well as handling a modest volume of dry cargo.

Figure 2 shows the typical annual movements in the two navigation channels. Whilst vessels greater than 42,000 tonnes displacement do pass under the bridge the number of transits is very few. This reveals the importance of a quantitative risk assessment to determine to what extent impact forces from the larger vessels should be taken into account in the design of the bridge.

The quantitative risk assessment forms the backbone for determining the actual ship impact forces on the structure. However, this risk assessment was carried out within the context of a wider study which included the following components:

- Consultation with marine control authorities and review of shipping regulations in place
- Review of previous marine risk assessments carried out in the Firth of Forth
- Establishment of database of vessel transits from Vessel Traffic Services (VTS) records
- Marine traffic forecast for 2041 design year based on UK port demand forecasts
- Establishment of GIS model of transit paths from VTS radar data
- Span and airdraft assessment
- Navigation simulations with local pilots
- Qualitative risk assessment, hazard identification and review of mitigation strategies
- Assessment of additional risk due to fire and explosion of impacting ships
- Assessment of impact of bridge on existing radar facilities

The full study is too involved to be described within this paper and many aspects are unique to the bridge site, instead we shall concentrate on the quantitative risk assessment since it is expected that the practical application of the Eurocode will be of particular interest to a wider audience.

2. Quantitative risk assessment methodology

2.1 Eurocode – an open ended design code

As the bridge is being designed to the Eurocodes it naturally follows that the quantitative risk assessment should be based primarily on Eurocode Part 1-7 [2]. This document provides a framework for assessment which in principle has many similarities to the AASHTO Guide Specifications [3] which have been widely used internationally.

The main similarities between the Eurocode and AASHTO are that a summation should be made for a design population of vessels transiting in a year and that for each vessel transit the probability of bridge failure should be calculated as the probability of the vessel becoming aberrant multiplied by the conditional geometric probability of the bridge striking a bridge component and the further conditional probability of that collision leading to failure. The calculated annual frequency of failure should be less than a predetermined tolerable value.

However, whilst AASHTO describes all of the necessary steps in sufficient detail to allow it to be readily implemented, the Eurocode is entirely open-ended and essentially requires the designer to decide from first principles or prior practice almost every aspect of the methodology.

2.2 Holistic or scenario based approaches

Although open ended, the Eurocode is clear that it differs from AASHTO on one fundamental point of principle. AASHTO adopts a holistic or statistical methodology whereby vessel aberrancy is considered *per bridge transit* and the geometric probability of collision is entirely independent of the circumstances of aberrancy. The Eurocode defines vessel aberrancy as being *per unit travelling distance* and indicates that the geometric probability of collision should consider the location where the vessel became aberrant. This leads the designer towards a scenario based or synthesis method whereby an attempt is made to determine the risk of collision based on assumed behaviour of the vessel due to a specific aberrancy scenario.

Gluver and Olsen [4] have compared the two methods with the conclusion being that neither is entirely satisfactory and Kunz [5] has noted the difficulty with the scenario based approach. The holistic method suffers from a sparsity of statistical data which leads to relatively simple models. This brings with it the danger of inappropriate incorporation of local conditions not envisaged in the original statistical derivation. On the other hand, with human error accounting for the majority of navigational accidents it is very difficult to model with accuracy the actual behaviour of a specific vessel in a scenario based approach, particularly if one then aims to integrate a large number of extremely diverse scenarios to obtain the overall project risk. Even for vessel aberrancy initiated by technical failure, the author believes that post aberrancy human intervention leads to a large degree of uncertainty in the scenario based approach.

2.3 A semi-holistic approach for the Forth Replacement Crossing

For this project, the navigational conditions in the vicinity of the bridge are complex, with bends in the navigation channels and significant obstructions, not least of which is the existing Forth Rail Bridge. The holistic model of AASHTO would not be adequate. Therefore, to address the principles of the Eurocode as well as overcoming the inherent difficulties in the scenario based approach a semi-holistic model has been developed.

The essence of the semi-holistic model is:

- Vessel aberrancy is considered at any point on the transit paths in the vicinity of the bridge leading to a large number of aberrancy scenarios (defined solely by the point of aberrancy).
- The post-aberrancy behavior of the vessel is considered in a holistic manner without attempting to explicitly track the path and velocity of the vessel taking into account specific human, mechanical and metocean factors.

The analysis is described mathematically by equation (1) which is an extended derivation of equation B.6 in [2]:

$$\begin{aligned} P_f(T) &= \sum n \cdot T \cdot \int \lambda \cdot p_g \cdot (1-p_a) \cdot (1-p_{obs}) \cdot (1-p_{ag}) \cdot P\{F_{dyn} > R\} dx \\ P_f(T) &\leq AF \end{aligned} \tag{1}$$

Where

$P_f(T)$ is the probability of failure within the reference period T

$\Sigma n.T$ is the design number of vessels classified by type, size, pilotage and tug assistance that utilize the channels passing under the bridge during the reference period

λ is the probability of vessel aberrancy per unit travelling distance

p_g	is the geometric probability of the aberrant vessel striking a bridge component if it reaches the line of the bridge
p_a	is the probability that the collision is avoided by human intervention
p_{obs}	is the probability that the vessel is prevented from reaching the bridge by an obstruction
p_{ag}	is the probability that the vessel runs aground before it reaches the bridge
F_{dyn}	is the impact force on the structure considering vessel size and impact velocity
R	is the resistance of the structure
x	is the coordinate point along the vessel transit path where the vessel aberrancy occurs
AF	is the acceptable probability of failure within the reference period

3. Probability of Collision

The model that has been developed is an extension of the normal distribution specified by AASHTO. For vessel transit paths normal to the bridge, the probability of collision is consistent with AASHTO. However, by considering the approach path of the vessel, a significantly modified probability of collision occurs if the inbound path is not straight and perpendicular. The principles of the model, stated qualitatively, are:

- At the time of aberrancy the vessel will be following a defined transit path.
- After aberrancy, the vessel will, on average, head in the same direction as it was travelling at the time of aberrancy.
- Notwithstanding the above, there will be some tendency for the vessel to deviate from this heading and that the further the vessel travels from the point of aberrancy the greater this deviation will tend to be.

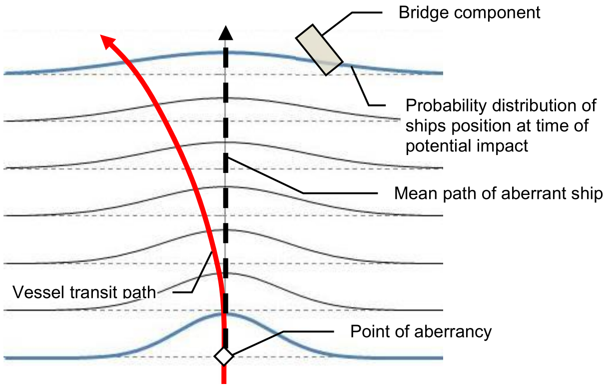

Fig. 3: Geometric probability model

These principles are illustrated in Figure 3. The initial position is assumed to be a normal distribution. After the aberrancy, the standard deviation of the position increases linearly with distance travelled. The geometric probability of collision is then calculated using the standard method of integrating the normal distribution of ships position considering the projected area of the pier and the beam of the vessel.

The geometric probability is modified by an additional factor which is probability of avoiding collision. This recognizes that if the aberrancy occurs at some distance from the bridge then there is a possibility that collision can be avoided by human intervention. Further modifiers are also introduced to consider obstructions in the Firth of Forth and the probability of running aground but these are site specific and are not integral to the semi-holistic model.

For orthogonal channels without obstructions or aberrancy modifiers the methods should show the following approximate equivalence:

$$\int \lambda \cdot p_g \cdot (1 - p_a) dx \cong BR \cdot PG \quad (2)$$

Where:

BR	is the AASHTO aberrancy base rate of 0.00006 per vessel transit

PG is the AASHTO geometric probability which is a normal distribution (with σ = LOA)

Figure 4 shows this comparison for the Forth Deepwater Channel for 200m Length Overall (LOA) vessels which is the upper bound of the vessels considered.

The outbound channel which is orthogonal and without obstructions shows a very good match over the region of interest outside of the navigation channel. Within the navigation channel the semi-holistic model shows a greater probability of aberrant vessels which is largely due to vessels which become aberrant immediately in front of the bridge and do not present a risk since they would pass under the bridge before being able to deviate sufficiently far from their path to strike a component.

Considering now the inbound channel the discrepancy between the AASHTO method and the semi-holistic based method is clear. The AASHTO method produces a normal distribution centred on the location the transit path passes under the bridge. The semi-holistic method has a double lobed distribution. Whilst one lobe is centred on the same location as the AASHTO method the second lobe is centred on the heading of the vessels prior to attempting the turn between the two existing bridges which happens to be more or less directly towards the South Tower where there is an order of magnitude increase in collision probability. The dashed line indicates the effect of the existing Rail Bridge which prevent some aberrant vessels from reaching the new bridge.

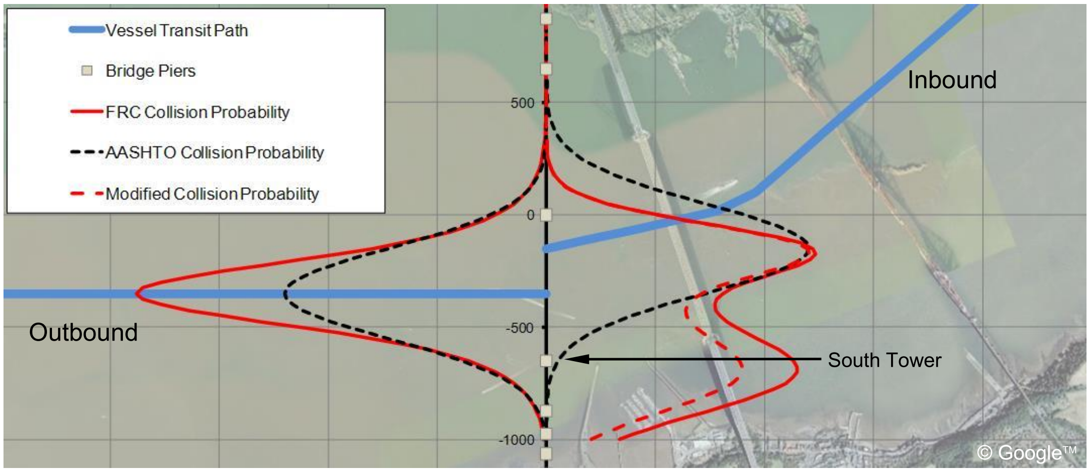

Fig. 4:Comparison between FRC and AASHTO collision probabilities

This comparison demonstrates good equivalence between the semi-holistic method and AASHTO for simple situations as well as the necessity to use a more complex method for the particular circumstances of the Forth Replacement Crossing.

4. Impact Speed

Vessel transit speeds in the vicinity of the bridge were determined by examination of VTS radar data. However, as described in AASHTO, review of accident case histories shows that aberrant vessels which collide with piers at large distances from the channel are usually drifting with the current whereas aberrant vessels located near the channel are moving at speeds approaching the speeds of the ships in the channel.

AASHTO provides a profile of impact velocity related to the distance from the centreline of the vessel transit path, reducing from the vessel transit speed in the channel to a minimum drift velocity at a distance of 3 x LOA. This was a necessary simplification based on the sparsity of accurate historical data and the selection of 3 x LOA to define the point at which the velocity equals the minimum was based on the observation that very few accidents other than drifting vessels have historically occurred beyond this boundary.

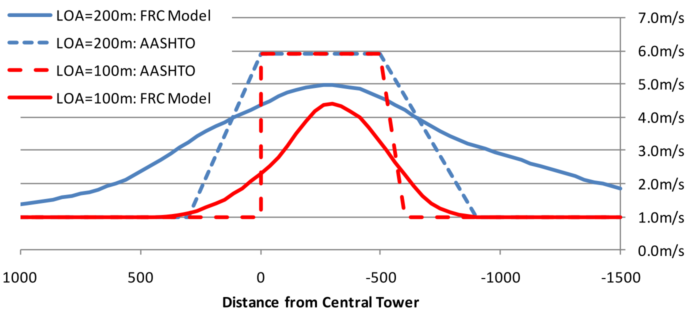

Fig. 5: Velocity profiles for FDC outbound path

For the semi-holistic model described in this paper it was considered more appropriate to relate impact speed to the distance between the point of aberrancy and the point of impact. The vessel is assumed to decelerate from the transit speed to a minimum drift velocity over a distance of 15 x LOA. This behaviour is only a statistical model since the semi-holistic method does not attempt to model the complete range of post-aberrancy scenarios.

By integrating all scenarios on a particular vessel transit path, the mean impact speed (weighted according to collision probability) is compared with the AASHTO velocity profile in Figure 5. For the areas of interest outside the navigation channel (where bridge piers are located) the impact speed is generally higher for the semi-holistic model which is therefore more conservative.

5. Conditional probability of failure

Larsen [6] describes two methods for calculating the conditional probability of failure, the "Heinrich Ratio" approach and the probabilistic approach.

The Heinrich Ratio approach considers the ratio of severe accidents to all accidents and is based on vessel-vessel collision statistics since there is insufficient statistical data on vessel-bridge collisions. This approach is adopted by AASHTO to develop a probability of collapse function, PC. The use of this function can cause stakeholders some concern since it can be concisely summarized that if the characteristic impact force is ten times the characteristic resistance the probability of collapse is only 10%. This relationship is not intuitive and the validity based on the vessel-vessel collision data is somewhat obscure.

A probabilistic approach has been followed to derive an explicit function for the conditional probability of failure. This approach involved defining a probability distribution function (PDF) for each of the impact force and the resistance and then convoluting the two functions to determine the probability that the force exceeds the resistance for different ratios of characteristic force to characteristic resistance. The two functions are indicated in Figure 6 together with the derived probability of failure function.

The probability distribution function for force is based on a composite of two normal distributions, one for head on bow impacts and one for glancing blow/broadside hull impacts. The probability distribution function for resistance is expressed as a normal distribution with the standard deviation determined considering three components:

- Material partial factors (which are not all equal to unity for accidental design situations)
- Difference between mean and characteristic material properties
- Variation in the point of application of the impact force

To elaborate the last component, the resistance of the structure is determined assuming that the impact force is applied in the most onerous position and orientation. However, the impact force may in reality be applied at a non-governing location so that the internal load effects are not as severe as assumed in the calculation. In other words the structure can resist a higher impact force if that force is applied at a non-critical location.

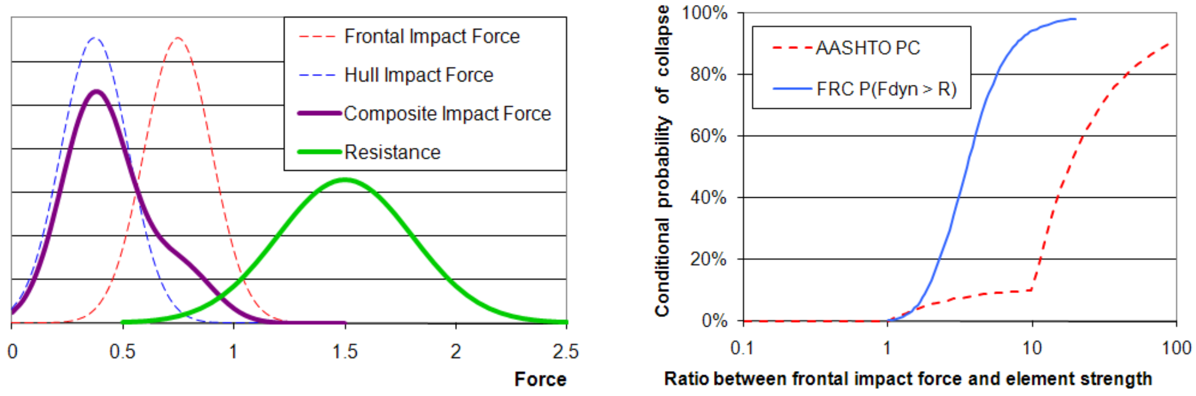

Fig. 6:Force and resistance PDF's for Fdyn = R (left) and the resultant collapse function (right)

6. Tolerable frequency of failure

6.1 Societal risk curves

Although the Eurocode provides principles to be considered in establishing tolerable failure frequencies it does not give specific values, nor does the UK National Annex.

Both individual risk and societal risk was considered for the project and the latter was found to be governing. Milloy [7] has described the how the Canvey Island Public Inquiry in the 1970's led to proposed societal risk curves for the UK [8]. A particular feature of these curves is that they are plotted with a slope of -1, displaying a neutral attitude towards major risks. This neutral attitude indicates that one accident with 100 fatalities is considered no worse than 10 accidents of 10 fatalities each. In either case the total number of casualties is the same. Although these risk curves have been proposed, they have not been adopted by UK legislation or design standards and therefore the project team was required to review and propose societal risk criteria.

Attitudes towards risk appear to have changed in the UK since the 1970's and the public generally displays a relatively strong aversion towards major incidents. The maximum tolerable risk level for the project was agreed based on a slope of -2 and intercepting the Canvey Island curve at 10 fatalities, the approximate boundary between major and minor incidents. The negligible risk level for the project adopted CIRIA guidance which is very close to the Canvey Island curve. The two curves together (Figure 7) indicate a narrowing band of broadly tolerable risk, with less scope for allowing the frequency of failure to increase on a cost-benefit basis as the consequences increase.

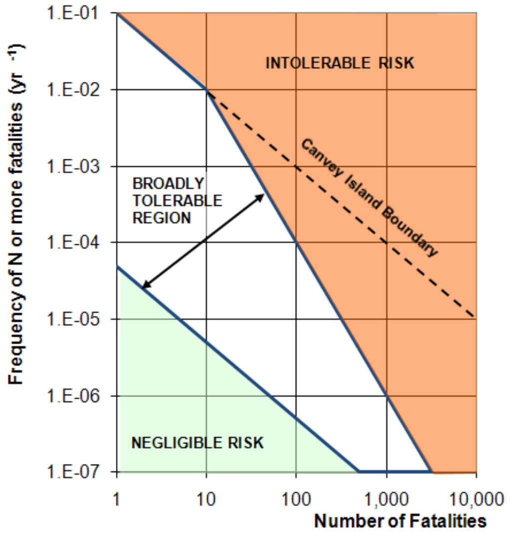

Fig. 7: Project Societal Risk Curves

6.2 Cost Benefit Analysis

Having established the risk boundaries, a cost benefit analysis was carried out to determine pier impact capacities which would provide an acceptable level of structural safety.

The principle of the cost benefit analysis is to compare the cost of reducing the failure frequency against the benefits of that reduction. Considering the highly regulated navigation controls in place there is little opportunity to further reduce risk by “soft” measures so the measures considered to reduce the failure frequency were enhanced structural strength and/or auxiliary ship impact protection such as sacrificial dolphins or artificial islands/reefs. The capital cost of these measures was estimated under a range of scenarios and compared against three quantified benefits:

- Value of prevented fatalities
- Direct demolition and reconstruction costs
- Indirect economic loss due to the bridge not being available during the reconstruction period

An economic model was established in order to calculate the expected present value of the stream of statistical benefits which would accrue over the 120 year design life of the bridge. Although not assessed in a quantified way, the additional environmental impacts of auxiliary ship impact protection were considered qualitatively in decision making.

The cost benefit analysis indicated that the capital costs outweighed the benefits of reducing the project risk below the maximum tolerable risk level. However, an As Low As Reasonably Practical approach to risk does not imply that decision making is bound to be purely mechanistic and the project Financial Advisory Group endorsed a set of pier impact capacities which were selected based on appropriate capital investment to achieve a reasonable balance between risk and cost.

7. Conclusions

A semi-holistic methodology for marine collision risk assessment has been developed to allow the ship impact design of the Forth Replacement Crossing to be carried out in accordance with the Eurocode, taking account of specific features of the site which make a holistic model inappropriate.

Adopting an As Low As Reasonably Practical (ALARP) approach has resulted in an estimated cost saving of EUR 115 M for the project in addition to environmental benefits. Fundamental to this approach was the requirement to establish societal risk curves appropriate for a major UK infrastructure investment in the 21st century.

8. References

[1] CARTER M., KITE S., HUSSAIN N., SEYWRIGHT A., GLOVER M. and MINTO B., Forth Replacement Crossing: Scheme Design of the Bridge. *Proceedings of 33rd IABSE Symposium, Bangkok*, 2009, pp. 382-383

[2] BSI British Standards. *Eurocode 1: Actions on Structures – Part 1-7: General Actions – Accidental Actions*. BSI, Milton Keynes, 2006, BS EN 1991-1-7:2006

[3] American Association of State Highway and Transport Officials, “Guide Specification and Commentary for Vessel Collision Design of Highway Bridges”, 2nd Edition, 2009

[4] GLUVER H. and OLSEN D., Current practice in risk analysis of ship collisions to bridges. *Proc. of the Int.Symp. on Advances in Ship Collision Analysis, Copenhagen*, 1998, pp. 85-96

[5] KUNTZ C.U., Ship bridge collision in river traffic, analysis and design practice. *Proc. of the Int. Symposium on Advances in Ship Collision Analysis, Copenhagen*, 1998, pp. 13-22

[6] LARSEN O.D., Ship Collision with Bridges – *The Interaction between Vessel Traffic and Bridge Structures*, IABSE Structural Engineering Documents No. 4, 1993.

[7] MILLOY C., An introduction to risk acceptance criteria. *Proceedings of the International Symposium on Advances in Ship Collision Analysis, Copenhagen*, 1998, pp. 97-102

[8] Health & Safety Executive, *Major Hazard Aspects of the Transport of Dangerous Substances*, H.M.S.O., London, 1991