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Navigational safety of inland vessels in the Międzyodrze and Szczeciński Węzeł Wodny area

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Abstract

The most important aspect of the transport of goods by water, including inland waterways, is navigational safety. Formal Safety Assessments (FSAs) are widely-adopted methods of risk analysis used to assess safety. By defining potential risks and describing event scenarios, FSAs allow the estimation and minimization of the level of risk of individual events. The current article presents the characteristics of accidents on inland waterways and the classification of accidents, with a discussion of their effects. After analysis, the research area was narrowly defined to vessels passing under bridges, and the threats arising from barges descending from the axis of the fairway. On the basis of the analysis, the authors have offered a risk assessment model of inland vessel collision with some element of navigational infrastructure during under-bridge passage. Event Tree Analysis (ETA) was used to carry out hazard identification.

Introduction

Inland waterway transport is considered to be one of the safest modes of transport. Its security is affected by factors such as the age and equipment of fleet vessels, the condition of roads, the competence of ships' crews, and the performance of checks and inspections (the exercise of supervision over shipping route users) (NIK, 2013). An additional factor in increasing safety on the water is the expanding Odra River Information Service (RIS), whose task is to monitor the movement of vessels and ensure that collisions are prevented. One of the main components of the RIS is a system for tracking ships. This system is based on such devices as an Automatic Identification System (AIS), radar, and CCTV cameras. These are the elements necessary to carry out surveillance of the movement of inland vessels. A FSA, a procedure which is intended to standardize the procedures around shipping safety (PRS, 2002), can also be a tool to support the safety of navigation in the Odra Basin and the Szczecin Water Node.

The first step in the FSA is to identify the risks that may occur during the navigation of the vessel on the test water. Hazard analysis can be carried out with one of five commonly-used methods (PRS, 2002; Jerzyło & Magda, 2011):

- Hazard and Operability Studies (HAZOP), otherwise known as the technique of words: intended to indicate deviation from acceptable levels on the basis of terms such as too high, too low, too little, too much, etc., it is principally used to determine how ship systems work.
- Fault Tree Analysis (FTA), or the construction of the unserviceability tree/tree error: a built-in graphic model indicates the relationship between damaged outboard equipment, human error, and causes.
- ETA, or construction of the tree: a built-in graphic model shows the consequences of an accident.

- Failure Mode and Effect Analysis (FMEA): used to determine those damages which have a significant impact on the work of the entire system (its efficiency).
- Technique for Human Error Rate Prediction (THERP), an analysis of human/navigator reliability: a model specifies wrong human decisions and related risks (Rausand, 2011).

An accident on inland waterways may be caused by the unintentional access of units to the axis of the fairway, or by their performing maneuvers such as passing or overtaking other units, input/output from ports, and docking/undocking at the waterfront (Gucma, 2013). Accidents on inland waterway shipping routes may also be caused by human error or the failure of navigational equipment. The probability event and type of effects both vary in the categories of accidents presented. A universal shipping safety assessment model proposed by the International Maritime Organization (IMO) consisted of five steps, namely hazards, risk assessment, determination of risk control tools, estimate of associated benefits and costs, and recommendations (IMO, 2002; Rausand, 2011). Figure 1 is a diagram of the FSA model.

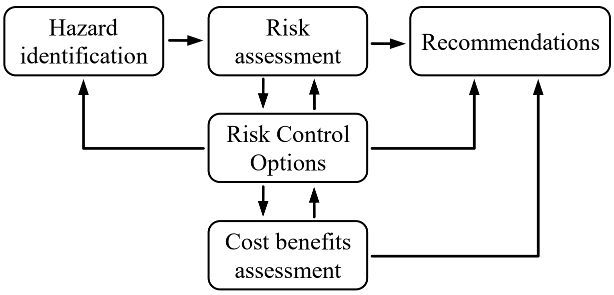

Figure 1. Five-step evaluation of navigational safety (Jerzyło & Magda, 2011)

A general Q3 (three-question) model is applied to determine the level of risk. This model takes into account the answer to the following three questions:

1. Q1 – what could go wrong?
2. Q2 – what is the probability that the situation will occur?
3. Q3 – what will the consequences be?

Answering these questions allows precise definition of the problem, and a determination of the probability of its occurrence and effects.

Inland accident characteristics

The risks arising from the operation of inland waterway vessels can be due to two types of threat, internal and external. The first group (those due to internal risk) concern inland waterway craft without reference to the environment. These include:

- fire;
- crack/damage to the unit's hull (for example, due to faulty loading);
- damage to equipment/construction/layouts.

The second group includes risks arising from the interaction of an inland waterway vessel with the environment. An inland waterway can be subject to five categories of maritime accidents, in which the ship can no longer maneuver due to human factors or a failure in the steering gear. They are:

1) grounding of inland vessel;
2) collision of inland vessel with a floating object on the fairway;
3) collision of inland vessel with another unit proceeding along the fairway;
4) collision of inland vessel with port/navigational infrastructure;
5) collision of inland vessel with another moored unit.

The current article analyzes the risks arising from the interaction of an inland vessel with the environment.

Grounding of inland vessel

The hull of a stranded barge touches the bottom, temporarily immobilizing the vessel. The vessel can be removed from shallow water spontaneously (by waiting for a higher tide) or with the help of tugs. The risk of stranding for units entering inland waterways was described as depending on (Gucma, 2014):

$$R_m = f_g \cdot S_m \tag{1}$$

where:
R_m – risk of grounding vessel;
f_g – frequency of grounding vessel;
S_m – effects of grounding vessel.

According to the World Association for Waterborne Transport Infrastructure (PIANC), the frequency of grounding is described as follows:

$$f_g = \frac{K \cdot l_c}{D} \tag{2}$$

where:
f_g – frequency of grounding vessel;
K – constant equal 10^5 per one passage;
l_c – length of the waterway;
D – width of the waterway.

Collision of inland vessel with a floating object on the fairway

Objects floating on inland rivers are considered floating navigation aids, marking navigation routes around drifts and obstacles. These objects do not control their own speed but, rather, move at the speed of the river current. Nevertheless, a collision with such objects can cause serious damage to the hull of the craft as well as objects, which can in some cases even be destroyed. The risk of a collision with a flying unit on the fairway can be described as depending on (Gucma, 2014):

$$R_{st} = f_{st} \cdot S_{st} \tag{3}$$

where:
R_{st} – risk of collision vessel with floating object on the fairway;
f_{st} – frequency of collision of inland vessel with floating object on the fairway;
S_{st} – effects of collision of inland vessel with floating object on the fairway.

According to requirements of the World Association for Waterborne Transport Infrastructure, the collision of an inland vessel with a floating object on the fairway is described as follows:

$$f_{st} = \frac{K \cdot p \cdot l_f}{w_f} \tag{4}$$

where:
f_{st} – frequency of collision with floating object on the fairway;
p – probability that a last chance maneuver did not help;
l_f – length of floating object [m];
w_f – distance of floating object from moving barge trajectory [m].

Collision of inland vessel with another unit proceeding along the fairway

The collision of an inland vessel with another unit proceeding along the fairway may occur as a result of passing or overtaking maneuvers. The effects of this type of conflict will depend on the speed at which both units are moving (side, bow, stern). The risk of collision with other units moving along the water track can be described as depending on (Gucma, 2014):

$$R_z = f_z \cdot S_z \tag{5}$$

where:
R_z – risk of collision of inland vessel with another unit proceeding along the fairway;
f_z – frequency of collision between units passing on the fairway;
S_z – effects of collision of inland vessel with another unit proceeding along the fairway.

Collision of inland vessel with inland infrastructure

The infrastructure of inland waterways is considered an element of port infrastructure (the construction of the waterfront), and such infrastructure (bridges, under bridges) can hit a barge while it is performing maneuvers. The risk of collision with a port infrastructure unit shows the following relationship (Gucma, 2014):

$$R_{zi} = f_a \cdot M_c \tag{6}$$

where:
R_{zi} – risk of collision of inland vessel with inland infrastructure;
f_a – frequency of collision of inland vessel with inland infrastructure;
M_c – value of the loss of infrastructure caused by accident.

$$f_a = \frac{n_a}{1000} \tag{7}$$

where:
f_a – frequency of collision unit with port infrastructure;
n_a – number of sea accidents.

Collision of inland vessel with another moored unit

The collision of an inland vessel with another moored unit may take place during mooring maneuvers, and when maneuvering in that part of the waterway along which the inland units are moored (Gucma, 2014).

$$R_{zp} = f_p \cdot M_p \tag{8}$$

where:
R_{zp} – risk of collision of inland vessel with another moored unit;
f_p – frequency of collision of inland vessel with another moored unit;
M_p – value of loss caused by collision.

The effects of accidents on inland shipping routes

In all cases of collision, it is necessary to specify the effects of the accident to determine risk. Depending on the type of conflict, a different model evaluation of the effects of the event must be used. The effects of the stranding of an inland unit are estimated on the basis of the damage sustained to the hull of the craft, and the losses incurred. Losses are principally the costs incurred as a result of:

- damage to the inland unit;
- loss/damage of cargo;
- the temporary closure of the fairway (if the unit was in the shallows, in a position that prevents the normal movement of other units);
- absence of load (an extension of cargo delivery time to the port of destination or reception);
- towing services.

The effects of a collision with a flying unit on the waterway depend to a large extent on the speed at which the unit is moving and the size of the object (Olanrewaju & Kader, 2013). The collision with a navigational marker may entail serious damage to the object and necessitate its repair or replacement. In the case of larger vessels, the craft's hull may be deformed. The consequences of a collision with another moving inland waterway vessel depend on both the speed of movement of the units and the angle, space, and depth. Moving inland waterway transport principally meet while:

- passing in two-way traffic lanes;
- overtaking.

The collision of two units can lead to serious tear-related damage to the hull plating, and even to the craft sinking. This type of event often entails the overall or partial loss of cargo. If the defective unit is not able to continue its journey to deliver its cargo at the port of destination, the cargo must be reloaded onto another barge. This involves additional expense, for example the charter of new barges and reloading costs.

The effects of a unit colliding with port or navigational infrastructure depend on the size of the damage arising as a result of the accident, and the relative costs. In the event of a collision with the quay during mooring maneuvers, the effects of deformation / damage to the hull of the craft and the costs associated with its repair are taken into consideration, as well as any damage to the waterfront. This type of collision could result in the detention of the vessel until events have been clarified, and it has been determined which of the parties shall bear the costs related to repairs. If the damage is very serious, the waterfront may be temporarily put out of use. As a result, support for other units and cargo will be suspended, with associated downtime costs. The consequences of a collision with other units moored on the waterfront are damage to the hulls of those units, and their temporary immobilization until events are clarified. Table 1 shows the accidents resulting from the interactions of inland vessels with the environment.

Methodology for the construction of a model risk assessment of inland vessel collisions with navigational infrastructure during under-bridge passage

In the Międzyodrze and Szczeciński Węzeł Wodny area, collision with navigational infrastructure is most likely to occur when vessels pass under bridges. In the case of certain bridge constructions, the passage of shipping is regulated by fences equipped with fender devices. The navigable width of the waterway at these sites is limited, requiring maneuvers to be carried out accurately, which is often difficult due to meteorological conditions (too large a drift) or because the vessel is traveling at too high a speed. One example of such a structure is a railway bridge on the Odra River. To assess the effects of collisions with coastal infrastructure (berthing elements) an evaluation of the kinetic energy of vessel impact in relation to the permissible kinetic energy absorbed by the elements of the infrastructure is generally applied. For the purposes of analysis, the unit is assumed to be a barge with a width of 8 m and a length of 21 m.

Table 1. Characteristics of inland water accident effects

Accident	Direct effect	Indirect effect
Grounding	Damage to the hull of the vessel	Costs of repair, towing service, loss of cargo
Collision of the vessel with a floating object on the fairway	Damage to the hull of the vessel, damage/destruction of the object	Costs of repair, costs of damage/destruction/repair
Collision of the vessel with another unit while passing on the fairway	Damage to the hulls of ships, towing services	Costs associated with the tug services, repairs, downtime of vessels on the fairway
Collision of the vessel with inland waterway infrastructure	Damage to the hull of the craft, damage to the infrastructure	Repair costs
Collision of the vessel with another moored unit	Damage to the hulls of ships, damage to/destruction of the mooring	Repair costs, the cost of the value of the lost cargo, replacing mooring lines

Hazards identification – ETA technique

To build a risk assessment model, the following assumptions were adopted:

- the crew is highly qualified and will take the appropriate decisions at the time of the threat;
- while passing under the bridge, the vessel does not collide with other units;
- the traffic of other units does not affect the movement of the analyzed vessel;
- the width of the navigable route was properly planned and marked.

The construction of the event tree starts with the determination of the initialization event. The event that initiates the risk during the under-bridge transition of the inland vessel is the deviation from the axis of the navigable route. This may occur as a result of bad meteorological conditions or damage to the rudder. The value of the loss is zero if the barge's grounding on the axis of the waterway occurred under the effect of wind and/or current. If the rudder damage causes loss of control, which in turn leads to the vessel stopping safely, this is considered a consequence of the losses associated with downtime (and load), the occupation of the fairway, rudder repairs, and towing services. At a time when safe stopping of the vessel is not possible, the damage to the steering gear could lead to striking the bridge spans. The value of the loss increases according to the force (kinetic energy) and angle of impact. This entails repairing or exchanging the existing navigational infrastructure (bridge spans and fender equipment) and hull plating on the vessel. A strong impact can lead to tearing, loss of plating in the buoyancy barge, and cargo loss. Figure 2 shows the model identification of hazards during the transition of an inland vessel under the bridge. The model was built using the techniques of ETA.

Probability of event occurrence

After the identification of hazards, the risk of each must be evaluated, for which Boolean logic elements were used. Successive events describe the consequences of the events of the initialization events. Each event has two branches that determine the success (positive) or lack of success (negative). The probability of events shall be between 0 and 1. The sum of the probabilities of the event and the absence thereof is equal to 1. Therefore, if the entire event is described by a collection of these, success can be described as $P(A)$, while failure is $1 - P(A) = P((A))$. Figure 3 shows the model identification of hazards prevented by using the probability of occurrences of individual events.

The events of each scenario (track) can be decomposed, taking into account probability.

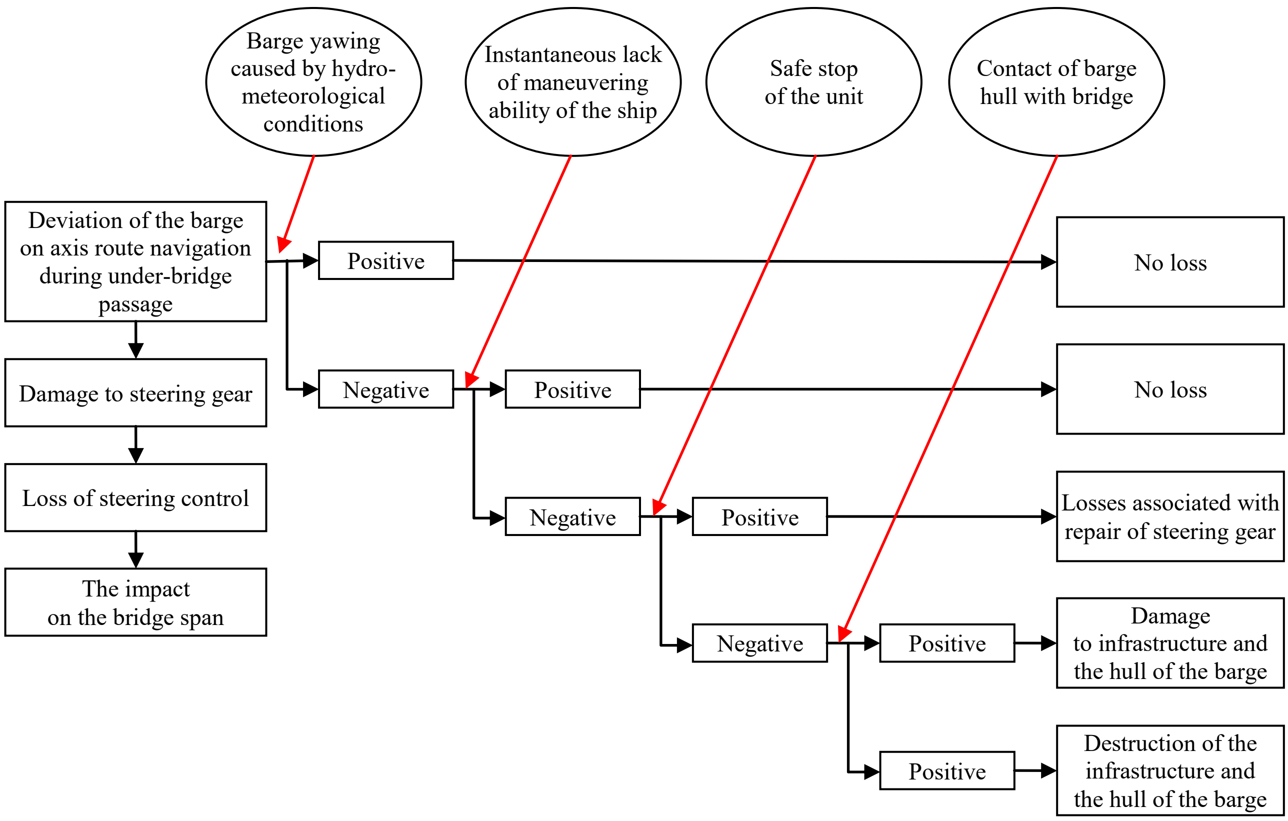

Figure 2. Model identification of hazards during under-bridge passage by an inland vessel, built using ETA techniques

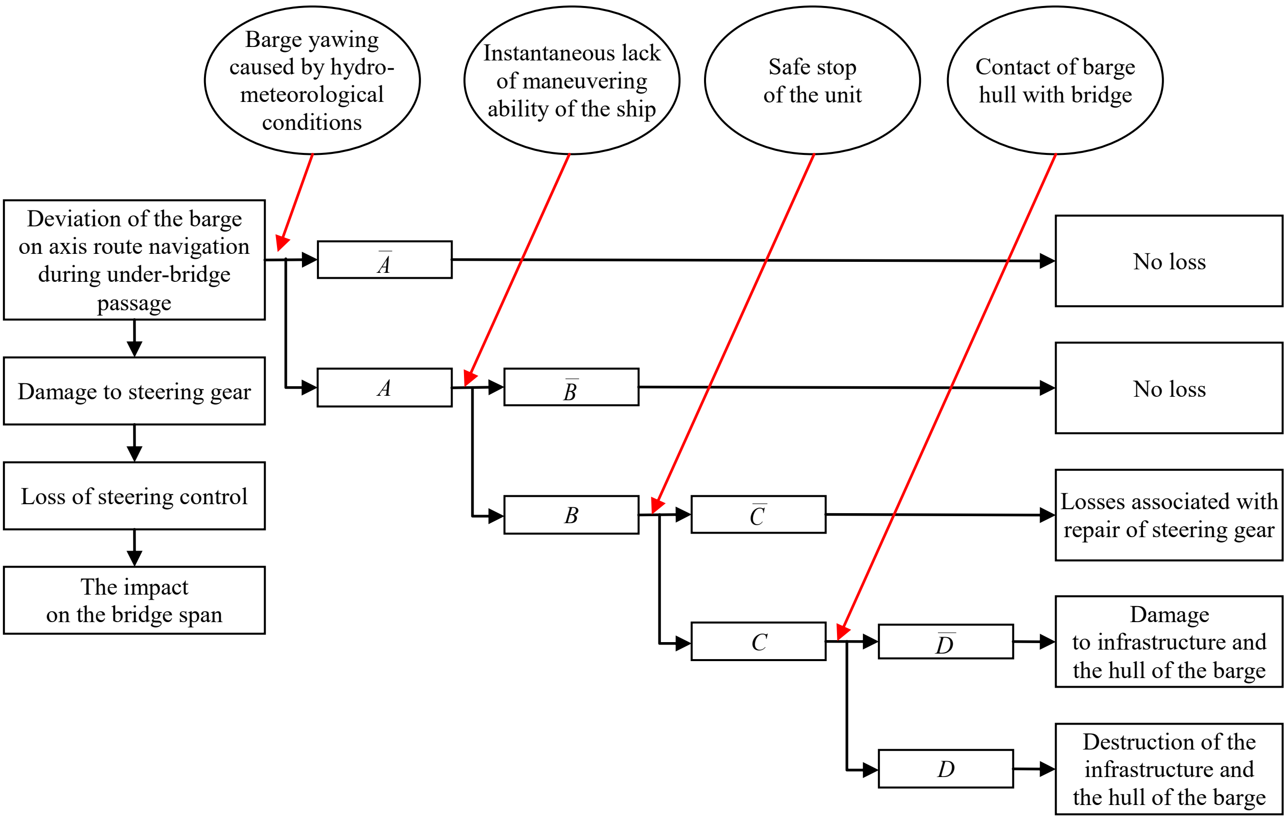

Figure 3. Model identification of risks during under-bridge passage of inland vessels, built with ETA techniques that take account of the probability of events

Path 1: Deviation of the barge from the fairway axis due to poor hydro-meteorological conditions:

Path1 – ($\bar{A}$), encountered with the probability of $P(\bar{A})$.

Path 2: Deviation of the barge from the fairway axis due to damage to steering gear (vessel under command while damage occurs).

Path2 – $A\bar{B}$, encountered with the probability $P(A)P(\bar{B})$.

Path 3: Deviation of the barge from the fairway axis due to damage to steering gear, causing loss of steering; however, the barge will be satisfactorily stopped.

Path3 – $AB\bar{C}$, encountered with the probability $P(A)P(B)P(\bar{C})$.

Path 4: Deviation of the barge from the fairway axis due to damage to steering gear, causing loss of steering which causes the barge to hit the bridge span.

Path4 – $ABC\bar{D}$, encountered with the probability $P(A)P(B)P(C)P(\bar{D})$.

Path 5: Deviation of the barge from the fairway axis due to damage to steering gear, causing loss of steering which causes the barge to hit the bridge span, with damage to infrastructure and barge hull.

Path5 – $ABCD$, encountered with the probability $P(A)P(B)P(C)P(D)$.

Quality criteria and risk matrix

Quality criteria are the basis for the creation of a risk matrix, and consist of a frequency analysis of events and their consequences. A frequency analysis can be carried out in three ways. The first is the analysis of archival data, on which the tendency of the occurrence of the event is based. The second is an estimate of the determination of the frequency of events from a system analysis. The third way is the use of expert knowledge in the field. Table 2 shows the frequency analysis of the events resulting from the initialization event.

Determination of losses takes into account the loss of human life, property, and environmental elements. In the case of collisions between vessels and inland navigation infrastructure during under-bridge passage, the main determinant of the losses is the

Table 2. Event frequency analysis

Frequency	Description
Extremely remote	Hitting the bridge span
Remote	Loss of steering
Reasonably probable	Damage to steering gear
Frequent	Deviation of the barge from axis of the fairway during under-bridge passage

Table 3. Event consequences analysis

Consequence	Description
Minor	Slight damage to the hull, navigational infrastructure
Significant	Damage to the hull with no influence on maneuverability, damage to navigational infrastructure
Severe	Temporary immobilization of the barge, serious damage to navigational infrastructure
Catastrophic	Tearing of the hull, loss of stability, loss of cargo, death of people, damage to navigational infrastructure

kinetic energy of the impact on the bridge spans. The weight of the consequences of the event depends on the force of impact and the damage it will cause. Model 3 shows the impact effects as tab units on the spans of the bridge.

After specifying the frequency of events and their consequences, a risk matrix model was created. The proposed matrix of the risk of collision between a vessel and inland navigation infrastructure during under-bridge passage takes into account the effects of the event. Table 4 presents a risk matrix model during the under-bridge transition of an inland vessel.

Table 4. Risk matrix model of collision between an inland vessel and navigational infrastructure

Incident (frequency extremely remote)	Consequences			
	Minor	Significant	Severe	Catastrophic
Collision of inland vessel with navigational infrastructure	Risk acceptable	Risk moderate	Risk moderate	Risk intolerable

Level (range) of risk depends on the frequency (probability) of the event and its effects (Urbański, Morgaś, & Specht, 2008). Having regard to these two factors, the risks are estimated at three levels: acceptable, moderate, and intolerable. Acceptable risk means the event with allowed risk level, where is no need to decrease it. Moderate risk is the range in which the risk may be reduced, but this involves disproportionately large costs in relation to the benefits achieved. However, the intolerable risk range means one which must be reduced, because there is a high possibility of a danger.

Conclusions

Inland waterway transport is an excellent alternative mode of transport for freight, especially heavy loads. Each trip unit, however, involves risk (the probability of the occurrence of an accident and its effects). Risk assessment is, increasingly, becoming the subject of research. The development of procedures is an effective way to increase safety.

The current article presents a methodology for estimating risks during the under-bridge passage of a vessel. ETA techniques enable the identification of hazards, which allowed the determination of the consequences of the event and analysis of their effects. The barge grounding on the fairway during an under-bridge transition was chosen as the initialization event. Consideration was also given to the occurrences of other possible events, and the risk matrix identified the worst consequences of these. The analysis carried out allowed for a safety assessment during the under-barge passage of a barge.

The methodology of the current research was taken from FSAs, a universal procedure which can be used for different types of units and different types of events.

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