Bibliographic review of vessel collisions on bridges: a case study in northern Brazil

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Abstract

Vessels operating in the Amazon and world fluvial navigation still face difficulties related to the lack of standardization and lack of compliance with the rules, resulting in collisions of river convoys over bridges. At the same time, there is an increase in demand for river transport over the years. Vessel collisions on bridges cause enormous socioeconomic damage to the municipalities located in the vicinity of the accident. In this sense, it is extremely important to verify the quantitative differences between various formulations of force and energy contained in the impact of vessels, found in the main international standards for bridge projects and in several studies of vessel collisions on works of art. Therefore, such formulations are applied to a case study of a convoy type sailing under the bridge of the Guamá River, in the north of Brazil.

Keywords: Collision; Floating Fenders; Energy Dissipation; Inland waterways.

1. Introduction

1.1 Contextualization of the problem

Restrictions on depth, river width, or even the passage of vessels under works of art, can be obstacles that imply restricted navigation. Such complications increase when there is low depth and high turbulence in the water flow regime in the vicinity of the pillars with relatively small free spans, thus increasing the probability of collisions of the vessels against the bridges. This type of setback has a huge impact on a region's transport logistics. At the same time, in the north of Brazil, the Amazon and Tocantins-Araguaia Hydrographic Regions experience an increasing rate of products transported by their inland waterways, according to data collected by ANTAQ (2021), indicated in Figure 1.

In view of this, considering the scenarios of increasing demand for inland navigation, there is a need to protect the bridges against the referred collisions, mostly from river convoys. This type of action is linked to fender designs for bridge protection, such as floating fenders and their design is based on estimates of the impact forces and energies that these structures must dissipate during the collision.

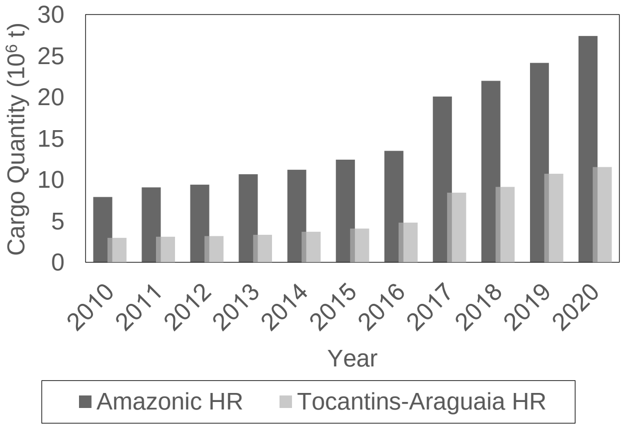

Figure 1. Evolution of cargo transported in northern Brazil, in millions of tons.

Consequently, it is necessary to use methods described by the main international standards for bridge designs, such as AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges (2009) and Eurocode 1991-1-7 (2006), as well as estimates indicated by major studies of vessel collisions on works of art.

1.2 Estimates of force and impact energy

The theoretical development of research on vessel collisions has differences for collisions from ships and those from barges. As one of the main authors who have developed knowledge about ship collisions against artworks, Svensson (2009) states that the only theoretical study that had relevance in this area was to Minorsky (1959), which had investigated the forces acting on head-on collision between two ships, checking a linear relationship between the volume of steel deformed between the two ships and the energy absorbed.

In the case of collisions against bridges or rigid walls, Woisin developed studies between 1967 and 1976, through several tests of impact on rigid walls, using 12 pairs of physical models of ships in the 1:12 and 1: 7.5 scales, and found that the dynamic impact forces had an amplitude magnified approximately twice in relation to the average value, between 0.1 and 0.2 seconds from the start of the collision.

Svensson (1982) concluded that the impact forces are proportional to the square root of deadweight (DWT) of the ship according to equation (1):

$$P = 0.88\sqrt{DWT} \pm 50\% \tag{1}$$

Investigations by Pedersen (1993) indicated that the maximum impact force, as a function of time, should be considered in the collision analysis of the ship and in bridge protection system designs, instead of the average impact force used by Equation (1). In this sense, the impact forces for vessels between 500 DWT and 50,000 DWT will be indicated by equations (2a) and (2b):

$$F = \begin{cases} F_0 \cdot \bar{L}[\bar{E}_{imp} + (5.0 - \bar{L})\bar{L}^{1.6}]^{0.5} & for \quad \bar{E}_{imp} \geq \bar{L}^{2.6} \\ 2.24 \cdot F_0[\bar{E}_{imp}\bar{L}]^{0.5} & for \quad \bar{E}_{imp} < \bar{L}^{2.6} \end{cases}, \tag{2a}$$

$$\overline{L} = L_{pp}/275,\, \overline{E}_{imp} = E_{imp}/1425 \text{ MNm},\, E_{imp} = \frac{1}{2} m_x V_0^2 \tag{2b}$$

Where, F is maximum collision load, in MN; F_0 is reference collision load of 210 MN.m; E_{imp} is energy absorbed by plastic deformations; L_{pp} is length of vessel, m; m is mass plus added mass (5%) with respect to longitudinal motion (10^6 kg); V_0 is initial speed of vessel, m/s (Wang et al. 2006).

In addition, the General Code for Design of Railway Bridges and Culverts (China, TB10002.1-99), provides an estimate of collision force given by:

$$F = \gamma \cdot V \sqrt{\frac{W}{c_1 + c_2}} \cdot \sin \alpha \tag{3}$$

Where γ is the kinetic energy reduction coefficient, where $\gamma = 0.3$ for bow collisions, and $\gamma = 0.2$ for other collision configurations; W is the vessel's displacement in tons; c_1 is the coefficient of elastic deformation of the ship; c_2 is the coefficient of elastic deformation of the collided component of the bridge, for example, a pillar. If there is no information about these coefficients, the Chinese standard specifies that $c_1 + c_2 = 0.0005$ m/kN (Wang et al. 2006).

In addition, on behalf of the Water and Shipping Directorate Southwest – Saar District, a study by Meier-Dörnberg (1983) allowed the prediction of impact force and deformation equations for barge collisions that collide with lock entrance structures, and bridge pillars.

As the main reference for AASHTO for the dimensioning of convoy type collisions in bridge projects, the authors' investigation also allowed the analysis of the direction and the height of the barge's rise on the slopes due to oblique impacts, and analysis of the stranding along the banks of the watercourse Meier-Dörnberg (1983 cited by AASHTO, 2009), despite this fact not be the focus of the results of this bibliographic review. In this sense, according to AASHTO Guide Specification (2009), the impact energy is the first factor that makes it possible to estimate the impact force for collisions from river convoys over works of art, and can be calculated from the equation (4):

$$KE = 500 \cdot C_H \cdot W \cdot V^2 \times 10^{-6} \quad [\text{MJ}] \tag{4}$$

Where KE is the vessel's collision kinetic energy considered in MJ; C_H is the hydrodynamic mass coefficient; W is the displacement of the vessel in t; V is the impact speed, in m/s.

In the calculations, the loaded displacement is considered, composed of the light weight plus the maximum weight of the load. The C_H coefficients are a function of the distance between the bottom of the vessel and the bottom of the river, as shown below:

- $C_H = 1.05$ for keel clearance $\geq 0.5 \times$ Draft
- $C_H = 1.25$ for keel clearance $< 0.1 \times$ Draft

For oblique collisions, the impact energy absorbed by the vessel or the bridge structure is defined as a function of an angle of attack α, between the vessel's centerline and the wall surface. In these cases, the impact energy is a portion of the frontal impact energy, and is a function of the friction coefficient between the vessel's hull and the wall, according to Svensson (1982), in equation (5):

$$E = \eta \cdot KE \tag{5}$$

Where E is the impact energy in MJ, and η depends on the angle of impact and the coefficient of friction between the ship's hull and the damaged structure. Whereas the barge hull is steel and it will collide with a concrete pillar, then the coefficient of friction is μ = 0.35, and η can be estimated from Figure 2.
Finally, for collision impact force from convoys can be estimated from equations (6) and (7):

$$F = \begin{cases} 60 \cdot a_B \cdot R_B, & \text{for } a_B < 0.1\,m \\ 6 + 1.6 \cdot a_B \cdot R_B, & \text{for } a_B \geq 0.1\,m \end{cases} \tag{6}$$

$$a_B = \frac{3.1}{R_B}\left(\sqrt{1 + 0.13 \cdot KE} - 1\right) \tag{7}$$

Where F is the impact force in MN; a_B is the depth of damage on the barge, in m.

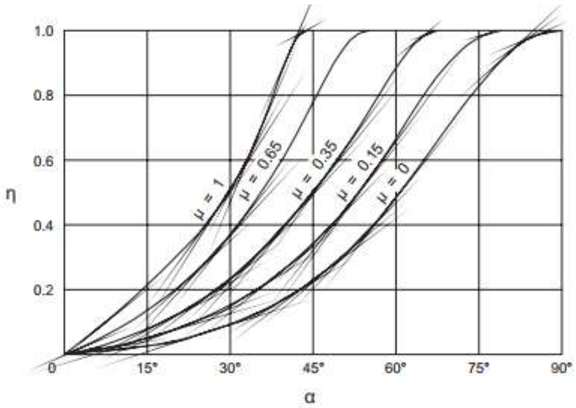

Figure 2. Portion of energy absorbed in the impact as a function of the angle of impact and the friction coefficient (Svensson, 1980).

Because the ferry-type used in the case study of the Guamá river have different dimensions of the ferry type used in studies indicated by AASHTO Guide Specification (2009), it will be necessary to correct the deformation of the bow by a R_B factor, which is the ratio the mouth of the barge actually used B_B and the standard barge B = 10.7 m, that is, $R_B = B_B/10.7$.
In parallel, Eurocode 1991-1-7 (2006) proposes that the impact force also depends on the kinetic energy of the collision on works of art. In this sense, the impact energy for frontal and oblique collisions will be, respectively, equations (8) and (9):

$$E_a = 0.5 \cdot m \cdot \mathrm{v}^2 \tag{8}$$

$$E_{def} = E_a\left(1 - \cos\alpha\right) \tag{9}$$

Equation (9) results in the same value as (8) because the frontal collision occurs when α = 90 °, that is, the direction formed between the center line of the aberrant vessel and the center line of the bridge superstructure.
From this, two possibilities are considered:

- If $E_{def} \leq 0.21$ MN.m, characterized by an elastic deformation of the barge structure, the dynamic impact force must be calculated by (10):

$$F_{dyn,el} = 10.95 \cdot \sqrt{E_{def}} \quad [MN] \tag{10}$$

- On the other hand, if $E_{def} > 0.21$ MN.m, featuring a plastic deformation of the barge structure, the dynamic impact force must be calculated by (11):

$$F_{dyn,pl} = 5.0 \cdot \sqrt{1 + 0.128 \cdot E_{def}} \quad [MN] \tag{11}$$

In addition, if it is necessary to model an impact force for the purposes of dynamic analysis of the impacted structure, the impact forces should be approximated as a half-wave sine pulse for $F_{dyn} < 5$ MN (elastic impact) or a trapezoidal pulse for $F_{dyn} > 5$ MN (plastic impact).

In the case of simulating the force as a trapezoidal pulse, the force considered should be the average between 5 MN and equation (10) or (11), depending on the criterion for strain energy ($E_{def} \leq 0.21$ or $E_{def} > 0.21$ MN.m).

For the European standard, the additional mass of the vessel that collides head-on can be estimated as 10% of the total convoy displacement, whereas for oblique collisions the additional mass must be 40% of the total convoy displacement.

2. Methodology

The impact forces and energies of a convoy-tipe sailing the Guamá River, in the state of Pará / Brazil, will be checked. A flowchart for the methodology used in this research is found in Figure 3.

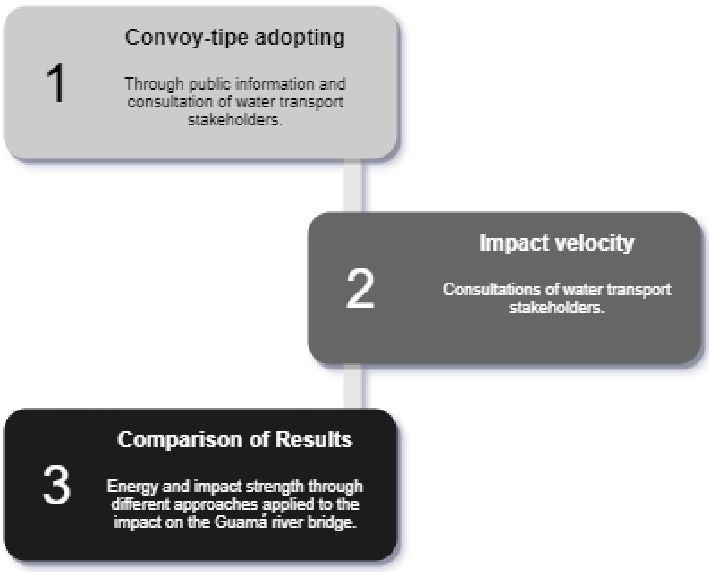

Figure 3. Flowchart of the steps used in this research. (Author, in press).

Firstly, this convoy type will be adopted based on information obtained from official agencies of the Brazilian government, such as the Ministry of Infrastructure (2017), but with the pusher to the dimensions most common among the main actors of the water transport in the said river, such as transport companies of raw material of plant origin.

Then, for the adoption of the impact speed on the bridge over the Guamá river, the most common navigation speeds on the Guamá river were also verified, and it will be 3 m/s, added to the average speed of the river current close to the bridge, 1.5 m/s, thus making the impact speed 4.5 m/s, representing a case with a realistic chance of the impact occurring.

Finally, the comparative focus between energies and forces for the impact on the bridge of the Guamá River, at a speed of 4.7 m/s, will be given among the main international standards for bridge projects, such as AASHTO Guide Specification (2009) and Eurocode 1991-1-7 (2006). However, the other estimates for impact forces, indicated by equations 2a-b and 3, despite focusing on the impact of merchant ships on bridges, will be used to verify the quantitative difference in such magnitudes from the impact of river convoys on the Guamá river bridge, in relation to the estimates indicated by those standards.

The results should also indicate the evolution of the impact force for different impact speeds, between 1 and 6 m/s, as well as for different impact force incidence angles.

2.1 Adoption of the convoy type for the Guamá river

The Guamá-Capim waterway is an important corridor for the transport of ores, mostly from the deposits of kaolin and bauxite, in addition to serving the movement of agricultural production, or other products of plant origin, from the region of Paragominas. The waterway's convoy type consists of four barges, (Padovezi, 2003), whose formation is called “1: 2: 2” (1 pusher, 2 rafts in the transverse direction and 2 in the longitudinal direction).

Convoys that sail on the Guamá river go to the Organized Port of Vila do Conde, in the municipality of Barcarena / PA, or even other cities that allow receipt of cargo transported. In addition, most convoys sail under the bridge of the Guamá River located on the PA-483 highway near the capital of the state of Pará and, according to SETRAN (2019), the bridge is 1950 m long, with 320 m span free between the two masts of the central span, as can be seen in Figure 4.

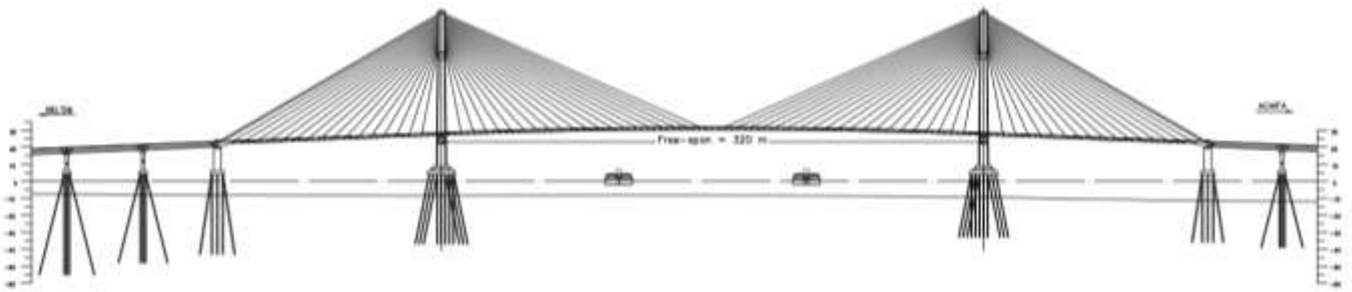

Figure 4. Bridge over the Guamá river. (Autor, in press).

In view of this, the convoy type used in the Guamá River to estimate energy and impact forces for different studies and standards for bridge protection projects, has the characteristics of Table 1, and is shown in Figure 5.

Table 1. Convoy type used in case study of Guamá river. (Author, in press).

Description	Total Length (m)	Beam (m)	Maximum Draft (m)	Loaded Displacement (t)
Pusher	18.8	6.3	1.5	113.88
Barge	50.0	8.0	2.5	900
Convoy	120.0	16.0	2.5	3600

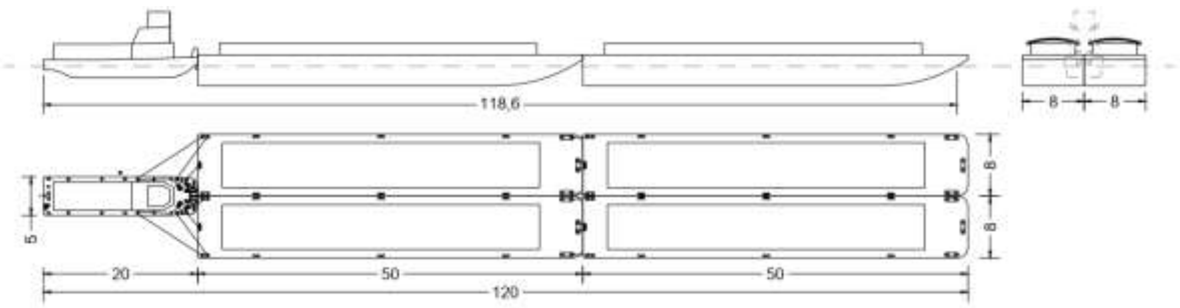

Figure 5. Convoy type used in this case study. (Author, in press).

Therefore, the total displacement of the convoy type during the impact will be Δ_{convoy} = 3600 + 113.88 = 3713.88 t

3. Impact Settings

Yuan (2005 apud AASHTO, 2009), from the University of Kentucky, indicated that placing the barges along the longitudinal length implies very conservative impact forces when using the formulas of the AASHTO Guide Specification (2009). In addition, when the barges are arranged over their widths, the mooring lines do not break and remain connected enough to transmit part of the energy contained in the collision.

Eurocode 1991-1-7 (2006) states that equation (9) for estimating impact energy applies to collisions up to 20°. However, for comparative purposes between the different studies, 4 impact situations will be considered, with speeds in an interval of 1 to 6 m/s according to the list and following and Figure 6, however, comparing values for the impact speed of 4.5 m/s:

- Lateral impact with α = 30°;
- Lateral impact with α = 45°;
- Lateral impact with α = 60°; and
- Frontal impact with α = 90°.

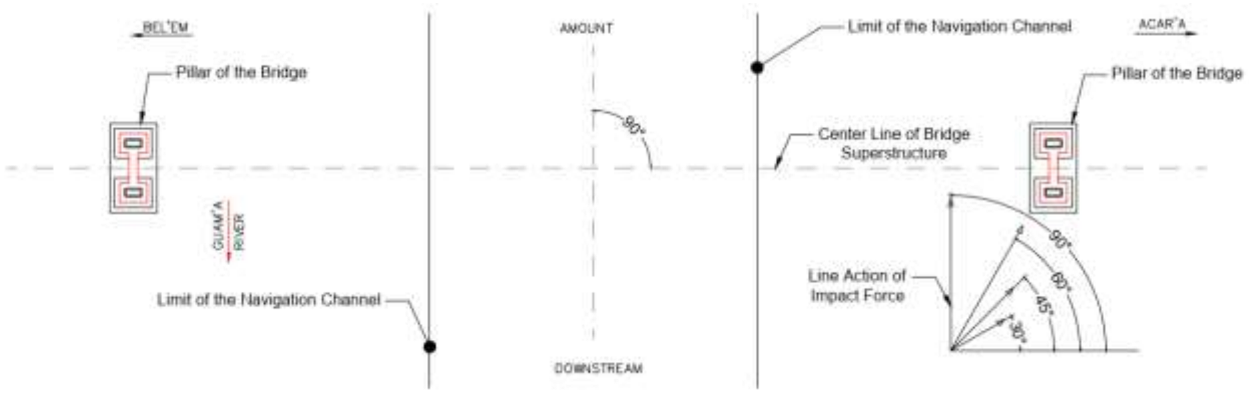

Figure 6. Different configurations for impact on the Guamá river bridge. (Author, in press).

4. Results and discussions

Protection of bridges for collisions of vessels against pillars of bridges should be a focus of the authorities in order to guarantee the safety of navigation and people who would be impacted by a possible interruption in the bridge from these setbacks.

In view of this, this bibliographic review seeks to verify and compare the different estimates of forces and impact energy resulting from a possible collision of a convoy type on the bridge over the Guamá river, where road and waterways are extremely important for the flow of goods, services and people in northern Brazil.

The results for energies and impact forces from the Figure 5 convoy, considering the AASHTO Guide Specification (2009) and Eurocode 1991-1-7 (2006) standards for the speed of 4.5 m/s are shown, in Figure 7.

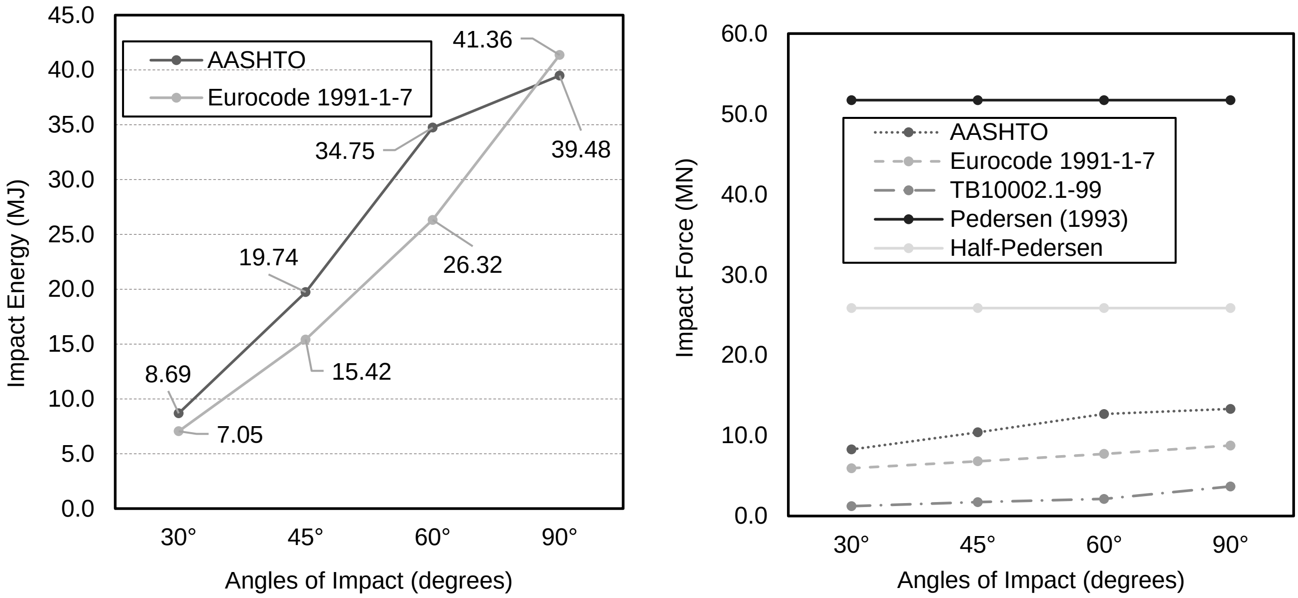

Figure 7. (Left): Impact energies in the Guamá river estimated through the main international standards. (Right): Impact force on the Guamá River from different studies and standards. (Author, in press).

For the impact on the Guamá river, it appears that the AASHTO (2009) standard is more conservative than the European standard in oblique collisions, probably due to the fact that these energies are a percentage of the frontal impact energy, according to equation (5) , that is, for the impacts of 30°, 45° and 60° considering the American standard, the energies were 8.69 MJ, 19.74 MJ and 34.15 MJ, while the energies estimated through the European standard for the same angles of incidence of impact are 7.05 MJ, 15.42 MJ and 26.32 MJ.

Due to the fact that the Guamá river convoy type has a 2x2 configuration and, consequently, is highly robust, the energies contained in the frontal impacts, through American and European standards, have high values, being 39.48 MJ for AASHTO Guide Specification (2009) and 41.36 MJ for Eurocode 1991-1-7 (2006), differing by 1.88 MJ.

Regarding the impact force, when comparing different approaches for estimating these magnitudes, Figure 7 (Right) presents the values for a speed of 4.5 m/s, using equations (2), (3), (6), and average force between

(10), or (11) if F_{dyn} > 5 MN.

In this sense, the impact forces of the convoy type on the Guamá river bridge for the different approaches are shown for impact speeds of 1 to 6 m/s, the maximum speed of which would hardly be reached by such convoys. The magnitudes are shown in Figure 8.

It can be seen, therefore, that the behavior of the convoy's impact force on the Guamá river bridge as a function of speed, is conservative for the approaches of Pedersen (1993) and AASHTO Guide Specification (2009).

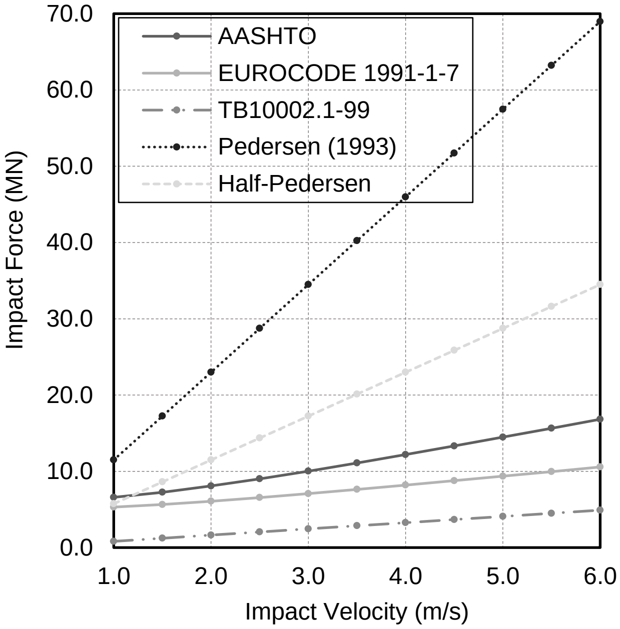

Figure 8. Impact forces for the Guamá River at different speeds, approaches and standards (Author, in press).

5. Conclusions

For impact energies based on the two standards, it appears that AASHTO Guide Specification (2009) is more conservative than the Eurocode 1991-1-7 (2006) standard, and the average difference between the energies at the different impact angles is 4.06 MJ for an impact speed of 4.5 m/s. The consequence of this fact is that the European standard offers a "slack" for the designer to use adequate safety factors for each project, based on dynamic analyzes obtained by his own simulations and, therefore, tending not to oversize the structures of the protection systems of bridges.

For frontal impact, the impact energies from AASHTO (2009) and Eurocode 1991-1-7 (2006) have close values, that is, 39.48 MJ for the American standard and 41.36 MJ for the European standard, a percentage difference 4.76% in relation to the American.

For the impact forces estimated through different studies, also for an impact speed of 4.5 m/s, the results for Pedersen (1993) have conservative values, a fact also indicated by Wang et al (2006), as well as the values of Half-Pedersen, who are also conservative for the convoy type of Guamá river.

Even so, the results for AASHTO (2009) are higher than those indicated by Eurocode 1991-1-7 (2006). The average difference between the magnitudes indicated by these two standards is 3.86 MN and, for frontal impacts, the magnitudes found were 13.32 MN and 8.77 MN for the American and European standards, respectively. The percentage difference is 34.16% compared to the American standard.

In addition, Wang et al. (2006) presented, in his research, equation (3) which resulted in values below those indicated by other studies.

It is concluded, therefore, that for proposals for protection systems of bridges against collisions of inland waterway convoys, the best approaches are those represented by the American and European standards, since these have close safety margins, a fact that provides confidence in the elaboration design of protection systems for bridge pillars, such as floating fenders.

It is also noteworthy that such floating systems projects must go through stages of dimensioning the structural arrangement through the rules of classifying societies, and the verification of the results obtained for impact forces must be carried out using numerical methods of analysis in engineering, such as finite elements, and laboratory tests on a small scale, in order to guarantee the reliability of the parameters used in the design of these fenders.

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