SHIP AND BARGE COLLISIONS WITH BRIDGES OVER NAVIGABLE WATERWAYS

by

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ABSTRACT

Highway and rail bridges that cross busy navigation channels near coastal ports and inland waterways pose unique risks to a nation's critical transportation infrastructure, and potential bridge collapse due to vessel collision often leads to loss of life and significant economic and political consequences. Recent decades have demonstrated the potential vulnerability of major bridge crossings over navigable waterways to catastrophic collapse due to extreme event loads. This paper will discuss ship and barge collision with bridges over waterways using lessons learned from historical accidents worldwide and analysis procedures for vessel collision assessments for new and existing bridges in the United States (AASHTO 2009 and AASHTO 2014). This paper also discusses the application of ship and barge collision risk analysis procedures to model complex navigation channel geometries near bridges and modern electronic navigation systems and port control procedures that potentially reduce the risk of collision.

1. INTRODUCTION

Vulnerability of critical infrastructures to extreme events have made headlines worldwide in the past decades due to structural failures, loss of life and financial damages associated with earthquakes, hurricanes, storm surge and waves, tsunamis, flooding and scour, vessel collisions, and terrorist attacks. For critical bridges, the risk and magnitude of such extreme events is often the controlling load case for the structure design. It was only after a marked increase in the frequency and severity of vessel collisions with bridges crossing navigable waterways that studies of the collision problem were initiated in the 1980s. Pivotal events spurring the change were collapses in 1980 of both the Sunshine Skyway Bridge (Figure 1) and the Tjörn Bridge (Figure 2).

In the period from 1960 to 2015, there have been 35 major bridge collapses worldwide due to ship or barge collision with a total loss of life of 342 people. The greatest loss of life occurred in 1983 when a passenger ship collided with a railroad bridge on the Volga River in Russia. One hundred and seventy six (176) people were killed when an aberrant vessel attempted to transit through a side span of the massive bridge. Most of the deaths occurred when a filled movie theater on the top deck of the passenger ship was sheared off by the low vertical clearance of the bridge superstructure's side span.

Figure 1: Sunshine Skyway Bridge Collapse, Tampa Bay, Florida, U.S. (1980)

Figure 2: Tjörn Bridge Collapse, Almo Sound, Sweden (1980)

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Relatively recent ship collision events have included the collapse of the Jiujiang Bridge in 2007 with 9 fatalities (Figure 3) and the Eggner's Ferry Bridge in 2012 (Figure 4). Eighteen (18) of the bridge catastrophes mentioned above occurred in the United States (U.S.), including the collapse of the Sunshine Skyway Bridge in which 396m of the main span collapsed and 35 lives were lost as a result of the collision by an empty 35,000 DWT (deadweight tonnage) bulk carrier (Figure 1). Recent collapse of U.S. bridges due to barge collision on the inland waterway system include the Queen Isabella Causeway Bridge in Texas (2001) which resulted in 8 fatalities, the I-40 Bridge in Oklahoma (2002) which resulted in 13 fatalities (Figure 5), and the Popps Ferry Bridge in Mississippi in 2009 (Figure 6).

Figure 3: Jiujiang Bridge Collapse, Xijiang River, Foshan, China (2007)

Figure 4: Eggner's Ferry Bridge Collapse, Kentucky, U.S. (2012)

Figure 5: I-40 Bridge Collapse, Oklahoma, U.S. (2002)

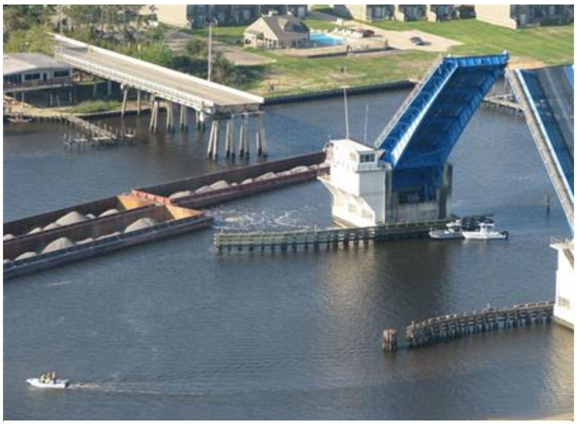


Figure 6: Popps Ferry Bridge Collapse, Mississippi, U.S. (2009)

One of the more publicized tragedies in the United States (U.S.) involved the 1993 collapse of a CSX Railroad Bridge across Bayou Canot near Mobile, Alabama. During dense fog, a barge tow became lost and entered a side channel of the Mobile River, where it struck a low-level railroad bridge causing a large displacement of the superstructure. The bridge collapsed a few minutes later when a fully loaded Amtrak passenger train attempted to cross the damaged structure. Forty-seven (47) fatalities occurred as a result of the collapse and train derailment.

It should be noted that there are numerous vessel collision accidents with bridges which cause damage that varies from minor to significant but does not necessarily result in collapse of the structure or loss of life. During a 2-week period in January 2016, there were 6 separate barge collisions with highway and rail bridges crossing the Mississippi River due to floodwater conditions. None of the collisions were catastrophic, but the bridges had to be closed temporarily for structural inspections and repairs. A United States Coast Guard (USCG) study of towing vessels and barge collisions with bridges located on the U.S. inland waterway system during the 10-year period from 1992 to 2001 revealed that there were 2,692 accidents with bridges (USCG 2003). Only 61 of these caused bridge damage in excess of US$500,000 (1,702 caused very minor damage with no repair costs to the bridge), and none resulted in fatalities. The study concluded that 90% of the barge tow accidents were related to human performance (78% to pilot error and 12% to other operational factors). Only 5% were related to mechanical problems, and for the remaining 5% there was insufficient information to assign a cause.

In addition to motorist and train disruption, structural damage and potential loss of life, significant environmental damage can also occur in a waterway due to oil and chemical spills as a result of vessel collision. An example includes the spillage of 644,000 liters of fuel oil in the Fore River, Maine in 1996 when a collision occurred with a bascule bridge pier of the Million Dollar Bridge that ripped a 9m hole in a loaded tanker ship (caused by an underwater protrusion of the concrete support pier footing). A large portion of the guide pile fender system was destroyed and the flare of the ship's bow imparted significant damage to the movable bascule leaves, causing closure of the bridge until repairs were made. Although the main cause of the accident was attributed to pilot error, a contributing factor was the limited horizontal clearance of the navigation opening through the bridge (only 29m). Another example includes the spillage of 203,000 liters of fuel oil into San Francisco Bay in 2007 when a container ship hit one of the main pier fender systems of the San Francisco-Oakland Bay Bridge during dense fog.

The 1980 collapse of the Sunshine Skyway Bridge was a major turning point in awareness and increased concern for the safety of bridges crossing navigable waterways in the United States. Investigations and research subsequent to the Sunshine Skyway and other major bridge accidents worldwide ultimately led to the development of the American Association of State Highway and Transportation Officials (AASHTO) *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* in 1991. For the first time, this landmark publication provided the bridge design community the procedures to evaluate the risk of vessel collision and estimate the magnitude of impact forces associated with ship and barge collisions. A second edition of the Guide Specification was developed (AASHTO 2009) to update and integrate lessons learned from the use of the original 1991 Guide Specification, incorporate Load and Resistance Factor Design (LRFD) bridge design methodologies, and include results from ship and barge collision research conducted since the original vessel collision publication. The Guide Specification provisions were subsequently adopted as a mandatory requirement of the primary U.S. bridge design code (AASHTO 2014). Unless otherwise noted, references to AASHTO vessel collision requirements in the remainder of this paper denote the AASHTO 2009 Guide Specification (AASHTO 2009).

It should be recognized that the USCG refers to ship and barge accidents as "allisions", which is technically correct as it involves an accident between a single moving object (ship/barge) and a stationary object (bridge). Whereas a "collision" is technically an accident between two moving objects. While respecting the technicality of the terms, the use of "collision" for ship/barge accidents with bridges is the publicly accepted usage for transportation-related accidents and is the term adopted by AASHTO in the bridge design specifications.

The AASHTO provisions and requirements represent a simplification of a very complex problem. Many of the requirements are based on lessons learned from historical accidents in which: 1) vessels impact bridges as they are transiting the waterway in the vicinity of the bridge during normal merchant marine operations, and 2) vessels impact bridges as a result of breaking loose from their moorings during a severe storm event and drift in the waterway due to winds and currents. These are two different design scenarios (load cases) in AASHTO and require two separate analyses for evaluating vessel collision impacts on different portions of the bridge.

After a summary of the basic AASHTO risk analysis equation, this paper will discuss: application of the AASHTO vessel collision principles for curved navigation channels near bridges, selection of the appropriate water depth and scour for use in the risk analysis for the evaluation of both tidal and non-tidal waterways, development of protection factors (PF) for use in the risk analysis, and the importance of considering vessel bow crushing when evaluating the consequences of potential local contact between an aberrant ship/barge bow with a bridge pier.

2. VESSEL COLLISION RISK ANALYSIS

2.1 Methodology

AASHTO provides three (3) alternative design methodologies (Methods I, II, and III) in order to furnish the bridge designer flexibility in establishing criteria for ship/barge collisions. Method II is the preferred design standard for critical structures and the method discussed in detail in this paper. However, there are situations where Methods I and III are appropriately employed.

Method I is a relatively simple, semi-deterministic procedure for selecting a design vessel and subsequently computing collision impact loads. It is particularly useful in shallow draft river waterways transited by barges and barge tows of approximately the same size. The procedure is less accurate (and usually more conservative) than the Method II analysis and is, therefore, not recommended for final design of critical bridges. However, Method I procedures are useful in defining boundaries of the navigation zone used in the Method II risk analysis. Method I procedures are also useful in providing an initial assessment of the magnitudes of impact forces while input data for the significantly more complicated Method II risk analysis procedures are collected and analyzed.

Method III is a cost-effectiveness procedure where benefit/cost analysis is combined with the risk of a potential bridge collapse to determine the applicable design vessel. This procedure is typically used in cases where it is not feasible (economically or technically) to either design a new bridge or retrofit an existing bridge to comply with the Method II risk acceptance criteria.

Method II is a probability based risk analysis procedure that can be used both for directly assessing the risk of collapse from vessel impact and developing vessel impact criteria for design. Using Method II procedures, a mathematical model is developed to estimate the annual frequency of bridge collapse based on the bridge pier/span geometry, ultimate pier strength, waterway characteristics, and the characteristics of the vessel fleet transiting the channel. The estimated risk of collapse can then be compared to predetermined acceptance criteria. Unless otherwise approved by the Owner for special situations, Method II should be used for all new bridge design.

AASHTO provisions specify an annual frequency of collapse of 0.0001 for critical bridges and an annual frequency of collapse of 0.001 for regular bridges based on risk comparisons with natural extreme events and engineering. These annual frequencies correspond to return periods of bridge collapse equal to 1/10,000 years, and 1/1,000 years, respectively. Critical bridges are defined as those bridges that are expected to continue to function after a major impact due to social/survival or security/defense requirements (typically these are iconic long span bridges). This does not imply that the structure is expected to last 10,000 or 1,000 years but that during the normal design life of the bridge (say 100 years) the risk of collapse due to collision by a vessel in the design fleet will be very small. It should be noted that the risk criteria for critical bridges is significantly greater than those for regular bridges and usually results in design impact loads associated with larger vessels transiting the waterway.

Various collision risk models have been developed to achieve design acceptance criteria. In general, the occurrence of a collision is separated into 4 events: 1) a vessel approaching the bridge becomes aberrant, 2) the aberrant vessel impacts a bridge element, 3) the bridge element that is hit fails, and 4) a protection factor based on bridge location and nearby waterway features. The AASHTO risk equation is shown below:

$$AF = (N)\,(PA)\,(PG)\,(PC)\,(PF)\,(GF) \qquad (1)$$

where

AF = Annual frequency of bridge element collapse due to vessel collision;

N = Annual number of vessel trips classified by type, size, and loading condition, that use the channel and can strike the bridge element,

PA = Probability of aberrancy (a measure of how often a vessel might go off-course),

PG = Geometric probability (if it goes off-course, will it hit part of the bridge?),

PC = Probability of collapse (if a bridge component is hit, will the bridge collapse?),

PF = Protection factor (are there land masses or nearby structures to protect the bridge?), and

GF = Growth factor to account for future increase (or decrease) in annual number of vessel trips (projection of vessel traffic to the mid-point of the bridge design life).

Once the input information for the analysis has been collected and developed (usually the most time consuming part of the process) the risk evaluation can be made relatively straightforward by using programs such as Microsoft Excel and Mathcad to automate the repetitive/iterative analysis process. As illustrated in Figure 7, the analysis is typically conducted in a matrix or table. In the first column, various types and sizes of ships/barges are arranged in rows in order of decreasing size. Values for the various risk components are then computed for each specific vessel type and an AF calculated for each row. This analysis is performed for each bridge pier and/or superstructure span as appropriate for the project as well as for vessels transiting both upbound and downbound (which can have differing speeds and water current conditions depending on transit direction). Once AF for each bridge pier or span component has been computed, the annual frequency of collapse of the total bridge can then be obtained by summing the AF's of each bridge component, vessel, and transit path in the analysis. The inverse of the annual frequency of collapse (1/AF) represents the return period (in years) of the failure event.

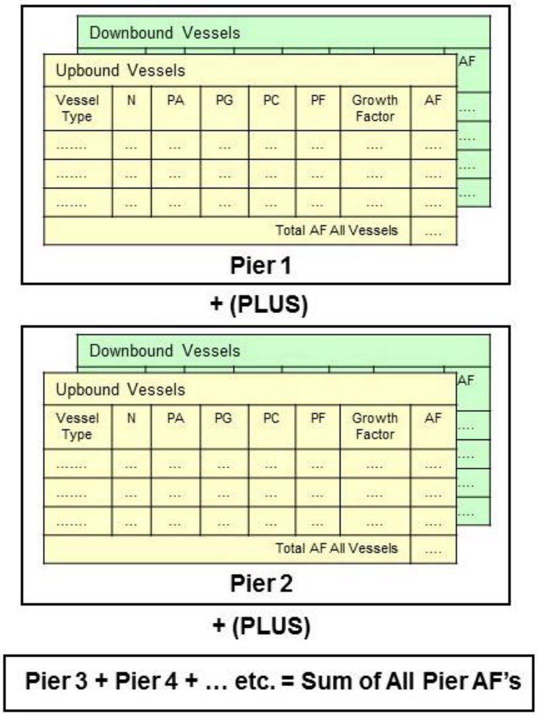


Figure 7: Computation of the Annual Frequency of Collapse (AF)

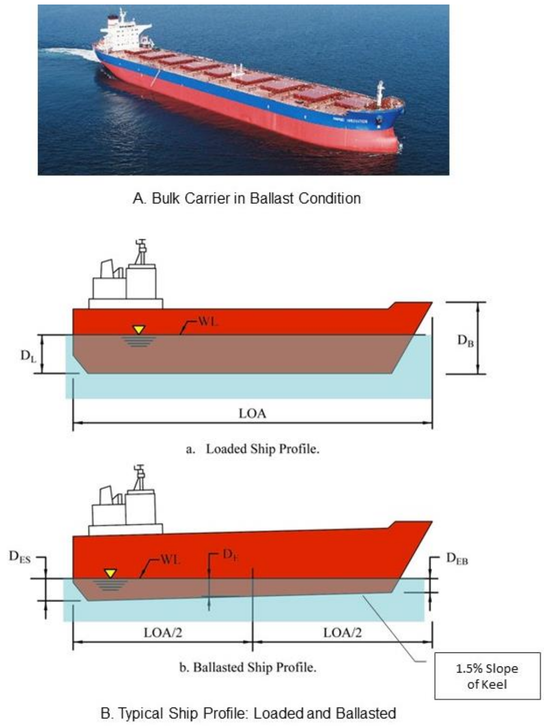


Figure 8: Ballasted Vessels

2.2 Vessel Fleet and Annual Frequency (N)

The number of vessels (N) that could potentially strike a bridge element is based on the available water depth and the actual draft of the aberrant vessel. Vessels transiting with drafts deeper than the available water depth will run aground before contacting the bridge, while those with drafts less than the available water depth have the ability to strike the bridge. The risk assessment must also include the effect of ballasted vessels transiting the waterway, since the draft at the bow is much smaller than the draft at the stern of the ship (Figure 8). The smaller draft at the bow can often reach bridge piers in shallow water at large distances (vessel length overall (LOA)) from where the stern starts to run aground. In general, tanker and bulk carrier vessels transit one-way loaded and one-way ballasted (or empty), whereas container ships, general cargo, and cruise ships are generally transiting loaded (or partly loaded) both upbound and downbound in a harbor or port.

With regards to water depth, the physical ability of a vessel to strike a bridge pier is based on the available water depth at the location of the pier and the draft of the vessel. For example, a loaded ship with a 10m draft would run aground before it could strike a pier in 6m of water, although the same ship transiting ballasted with a 5m draft at the stern and a 2.5m draft at the bow could potentially strike the pier. The ability of a vessel to "plow" through underlying soft soils without a significant decrease in speed must also be considered when establishing available water depths at bridge piers. In the absence of a more detailed vessel grounding analysis, a rule-of-thumb utilized by the authors is to assume an additional 1m of water depth to account for very soft surface material that may exist on the bottom of the waterway.

After waterway data is collected, the vessel fleet (ships and barges) transiting the navigation channel at the bridge location is subdivided into categories (usually 5,000 DWT increments) for the risk analysis. Vessel characteristics are developed for each category including; length overall (LOA), beam (width), drafts at the bow and stern (loaded and ballasted); displacement tonnage; heights above water level (bow, deckhouse and mast); and transit speeds (upbound and downtbound). Characteristics should also include the layout of ship bow overhangs, particularly for cruise and container ships, which often have large flares of the main deck extending over the bulbous bow at the waterline. Automatic Identification System (AIS) information for vessels transiting a waterway is an important source of data used to estimate the frequency of vessels, vessel tracks in the waterway, and operating speeds as they pass under the bridges. An example of plotted AIS vessel tracks is shown in Figure 9.

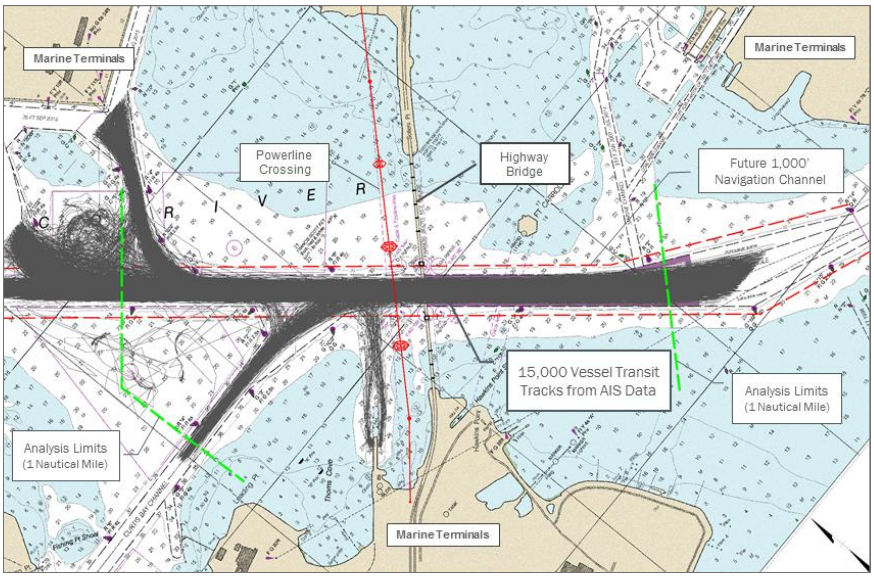


Figure 9: AIS Vessel Tracks at Bridge Location

2.3 Probability of Aberrancy (PA)

The probability of aberrancy (PA) is a measure of risk that a vessel is in trouble and may stray off-course as a result of pilot error, adverse environmental circumstances, or mechanical failure. The most accurate procedure for determining PA is to compute it using long-term vessel accident data (groundings, collisions, and rammings) in the waterway and statistics on the frequency of vessel traffic during the same period of time. An alternate procedure for calculating PA can be performed by using the following AASHTO equation:

$$PA = (BR)\ (R_B)\ (R_C)\ (R_{XC})\ (R_D) \qquad (2)$$

where

BR = Aberrancy base rate developed from historical accident data on waterways worldwide (assumed 0.6×10^{-4} for ships and 1.2×10^{-4} for barges),

R_B = Correction factor for bridge location,

R_C = Correction factor for currents acting parallel to vessel transit path,

R_{XC} = Correction factor for cross current acting perpendicular to vessel transit path, and

R_D = Correction factor for vessel traffic density.

The correction factor for bridge location (R_B) is computed based on the relative location of the bridge to one of three waterway regions (straight, transition, and turn/bend).

Correction factors for currents acting parallel (R_C) and perpendicular (R_{XC}) to the vessel transit path are based on equations provided in AASHTO. The parallel current component (V_C) and perpendicular current component (V_{XC}) are computed from the geometric relationship between the orientation of each vessel transit path or independent channel leg (see following discussion related to complex channel geometries) and the direction of the current.

The correction factor for vessel traffic density (R_D) in the immediate vicinity of the bridge is determined by whether the structure is located in a low, medium, or high density area.

Modern Navigation Practices: The AASHTO vessel aberrancy base rate (BR) assumes a single local pilot onboard ships transiting bridges in coastal locations and no tug assistance. The existing AASHTO provisions do not include consideration of new safety measures based on modern navigation systems, vessel design, and regulatory requirements (crew training and certifications, vessel safety inspections, maneuvering restrictions, etc.) that have occurred since the original adoption of AASHTO's vessel collision design provisions published in 1991. The Code also does not provide guidelines for modelling additional navigation restrictions that are sometimes imposed by Government Agencies such as requirements for certain vessels to have multiple pilots, tethered tugs, daylight transits only, speed limits, and visibility restrictions.

For the risk assessment of major bridges, it is important to include the effects of the above factors in potentially reducing the risk of collision. The aberrancy base rates in the risk assessment should be adjusted to reflect site-specific vessel operating practices and regulatory requirements in the navigable waterway. Adjustments to the aberrancy base rate may depend on the size, type and loading condition of the transiting vessels; the number of pilots; vessel operations; tethered tug escort; water currents; traffic density; transit speed and current restrictions; daylight and visibility restrictions; Vessel Traffic Service (VTS); electronic navigation tools (EDIS and other navigation aids and devices); and Port State Control (PSC). The magnitude of each adjustment can be established based on Code recommendations, published research, and previous risk studies that have been accepted by federal agencies as appropriate for similar marine risk analyses. Table 1 shows the site-specific recommended adjustments to BR for vessel collision risk assessments conducted for two highway bridges in Vancouver, Canada (Homes & Knott 2018).

Item/Description	Adjustment Factor	Discussion
Vessel Traffic Service (VTS)	0.80	20% reduction in risk attributed to VTS and mandatory vessel participation (Trans Mountain 2013)
Electronic Chart Display and Information System (ECDIS)	0.81	Compliance with international ECDIS requirements are mandatory for all ships by July 2018. The adjustment is based on 1/2 of the 38% reduction attributed to ECDIS because of the overlap with the reduction due to pilots onboard the vessel (Trans Mountain 2013).
Other Navigation Aids	1.00	Additional potential risk reductions include (Trans Mountain 2013): AIS (2-5%); ENC (0-13%); Conventional ATNs (0-13%); DGPS (0-8%); and PPU (0-10%). For purposes of vessel collision risk analysis, these potential reduction factors are sometimes not included to be conservative.
Port State Control (PSC)	0.94	PSC includes the inspection of foreign ships to verify compliance with international regulations on the condition of the ship, equipment, crew manning and operations (including rest periods). Studies have demonstrated that PSC activities reduce the rate of vessel accidents in waterways. The adjustment is based on 1/2 of the 12% reduction attributed to PSC because of the overlap with the reduction due to pilots onboard the vessel (Trans Mountain 2013).
Pilotage - 1 Pilot	1.00	The code base rate assumes a single pilot; therefore, a further reduction is not applicable.
Pilotage - 2 Pilots	0.54	46% reduction in risk attributed whenever a second pilot is required onboard a vessel (Trans Mountain 2013).
Daytime Only Transit Restriction	0.50	Value based on Larsen 1993 which states that the rate of collision/grounding accidents at night are 4 times the probability of such accidents in daytime (which implies a 75% reduction in risk or a reduction factor of 0.25). For purposes of the vessel collision risk assessment, a conservative value of 0.5 was used.
Visibility Restrictions	0.50	Value based on Larsen 1993 which states that the rate of collision/grounding accidents in fog when the visual range is less than 200m has been found to be 100 times the risk in clear weather. Visibility studies in Dover Strait, United Kingdom by Wheatley (Larsen 1993) found that reduced visibility increased the accident rate by 4.4 times as compared to clear visibility conditions (which implies a 77% reduction in risk or a reduction factor of 0.23). For purposes of the vessel collision risk analysis, a conservative value of 0.5 was used.
Passenger / Cruise Ships	0.17	Value based on Larsen 1993 which states that vessel accident studies in Japanese waters indicate that passenger vessels are 6 times safer than cargo ships and tankers (which implies an 83% reduction in risk or a reduction factor of 0.17).

Table 1: Example of BR Adjustments for Modern Navigation Practices

2.4 Geometric Probability (PG)

The geometric probability (PG) is the conditional probability that a vessel will hit a pier given that it has lost control (is aberrant) in the vicinity of the bridge. The method of computing PG is based on a normal distribution curve, with the mean located at the centerline of assumed vessel transit path and a standard deviation equal to the length overall (LOA) of the design vessel under consideration. Note that bridge elements located beyond 3 standard deviations from the centerline of vessel transit path do not influence the geometric probability of collision. The area under the normal distribution curve bounded by the limits of the centerline of vessel contacting either side of the pier is equal to the geometric probability of collision (Figure 10). As can be interpreted from this figure, increasing the distance between piers can significantly reduce the value of PG since the collision zone would be contained within the tail area of the normal distribution curve.

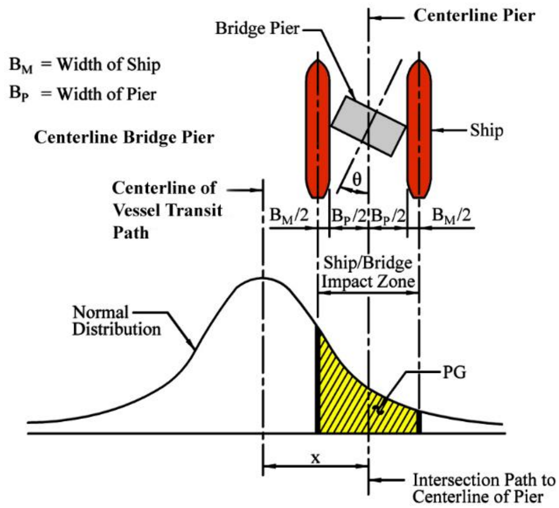


Figure 10: Geometric Probability of Pier Collision

<u>PG Adjustment for Tethered Tugs:</u> In some waterways, tug assistance for ships is required for transiting portions of the navigation channel. Where required during vessel transits, tethered tugs provide an extra measure of security related to potential vessel collision with bridges as tugs assist in keeping an aberrant ship in the navigation channel. For bridges located in areas where mandatory tug assistance is required for ships the AASHTO Method II risk analysis procedures for PG should be adjusted. For purposes of a risk assessment study only tugs tethered to the ship are considered. Because of potential time delays in hooking up with a ship near the bridge location, escort tugs and tugs of opportunity should be excluded from the risk assessment.

Within the context of the AASHTO procedures for estimating the risk of vessel collision, the use of tugs may have a slight benefit in reducing the PA base rate (minor because the major cause of aberrancy is human error onboard the ship). However, the primary benefit will be to the PG factor in reducing the ability of an aberrant vessel to leave the navigation channel as the tugs can push the vessel back into the channel and keep it away from the bridge. The following equation was developed by Moffatt & Nichol based on navigation simulations to model the effect of tethered tugs on PG by introducing an adjustment factor (r_{tug}) to reduce the standard deviation (σ) based on a tug safety factor (f_{tug}), width of the channel (w), vessel LOA, and properties of a standard normal distribution (ϕ).

$$r_{tug} = \frac{0.5w}{loa\Phi^{-1}\left(1 - \frac{1 - \Phi\left(\frac{0.5w}{loa}\right)}{f_{tug}}\right)} \tag{3}$$

A tug safety factor (f_{tug}) of 2.0 has been used in previous vessel collision studies based on Trans Mountain 2013 and other ship navigation studies. It could be argued that the tug safety factor might be much higher (exceeding 3 or 4) for ships with tethered tugs that are moving relatively slowly in the waterway. Although the tug adjustment factor (r_{tug}) varies based on vessel size, the typical reduction factor for ships in the vessel fleet is a modified standard deviation of approximately 1/3 of LOA (0.33). The effect of the adjustment to PG is shown in Figure 11. The use of a reduced standard deviation causes the spread of the normal distribution to “peak” closer to the mean (channel centerline). This reduces the PG associated with bridge piers and spans when compared to PG estimates without the adjustment. It should be noted that adjustment in the standard deviation used to estimate PG for ships with tethered tugs are also made to the standard deviation used in the vessel speed distribution in AASHTO 2009.

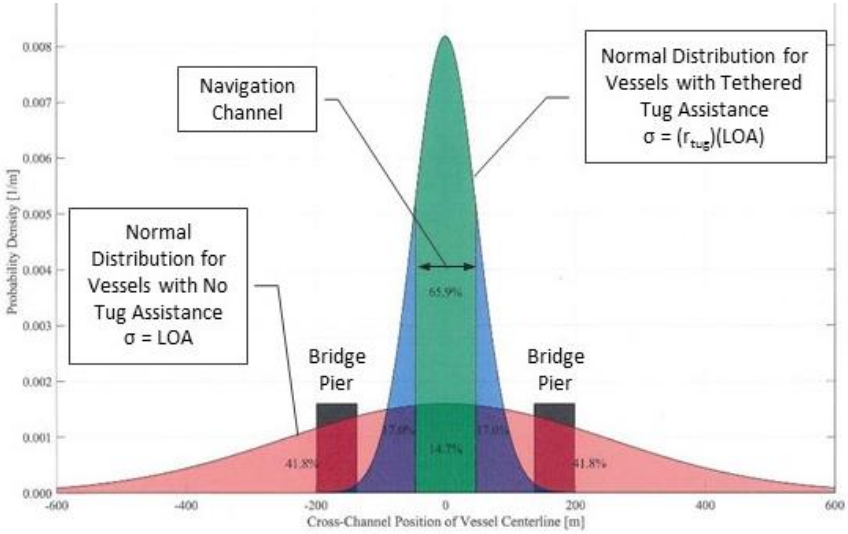


Figure 11: Tethered Tug Adjustment Factor

2.5 Probability of Collapse (PC)

The probability of bridge collapse (PC) once an aberrant vessel has struck a pier is a function of many variables including vessel size, type, bow shape, speed, direction of impact, and mass. It is also dependent upon the ability of the pier to resist collision impact loads. Based on historical accident data, the probability of collapse is computed according to the ratio of bridge element ultimate strength/capacity (H) to the vessel impact force/demand (P) in accordance with equations provided in AASHTO 2009. Note that the ultimate strength/capacity (H) is typically related to the overall “global” resistance of the bridge element being investigated. Therefore, under this criteria, localized damage would be deemed acceptable so long as it does not compromise the structural integrity of the system. From the equations provided in AASHTO, the following observations can be made:

- In cases where the pier capacity exceeds the design vessel impact force (> 100%), the probability of bridge collapse becomes 0.0
- In cases where the pier capacity is in the range of 100% to 10% of the design vessel impact force, the probability of bridge collapse varies linearly from 0.0 to 0.10
- In cases where the pier capacity is in the range of 10% to less than 0.1% of the design vessel impact force, the probability of bridge collapse varies linearly from 0.10 to 1.0

2.6 Protection Factor (PF)

The protection factor (PF) is used in the risk analysis to adjust AF for full or partial protection of individual bridge piers or span components (regardless of the actual water depth) from vessel collision due to protection measures or shielding associated with existing or new site conditions. Examples of protection measures include: an existing upstream or downstream bridge providing protection from impacts in one direction; a feature in the waterway, such as a shoreline or peninsula extending out on one side of the bridge that might block vessels from impacting a pier; a wharf or other structure near the bridge that might protect some of the piers; or protection measures installed at the bridge, such as dolphins or islands placed around piers to reduce the AF to acceptable levels. Values for PF may differ from pier to pier and may also vary depending on the direction of vessel traffic. The use of PF provides an important tool in evaluating the risk of ship/barge collision with bridges and in the development of effective and cost-effective protection measures if required by the risk analysis.

Similar to geometric probability (PG), the method for computing PF is based on a normal distribution curve, with the mean located at the centerline of assumed vessel transit path and a standard deviation equal to 30 degrees of rotation from the transit path. Therefore, at 3 standard deviations from the centerline of transit path, the vessel would effectively be traveling perpendicular to the bridge element and would no longer influence the protection factor. The area under the normal distribution curve is bounded by the protection angle (ϴ) provided on either side.

AASHTO provides an example of how PF is estimated for a large diameter dolphin structure placed in front of a bridge pier. The same protection principle is illustrated in Figure 12 for a bridge located on a narrow inland waterway, where a pier is situated in the water but close to the shoreline. The landside of the bridge provides protection for the pier from collisions in that particular direction, since aberrant barge tows outside of the channel would run aground. The level of protection provided by the landside can be calculated as shown in Figure 12, where vessel collision trajectories are estimated using a normal distribution based on a standard deviation (σ) equal to 30 degrees (0 degrees represents a head-on collision and 90 degrees a complete sideways collision).

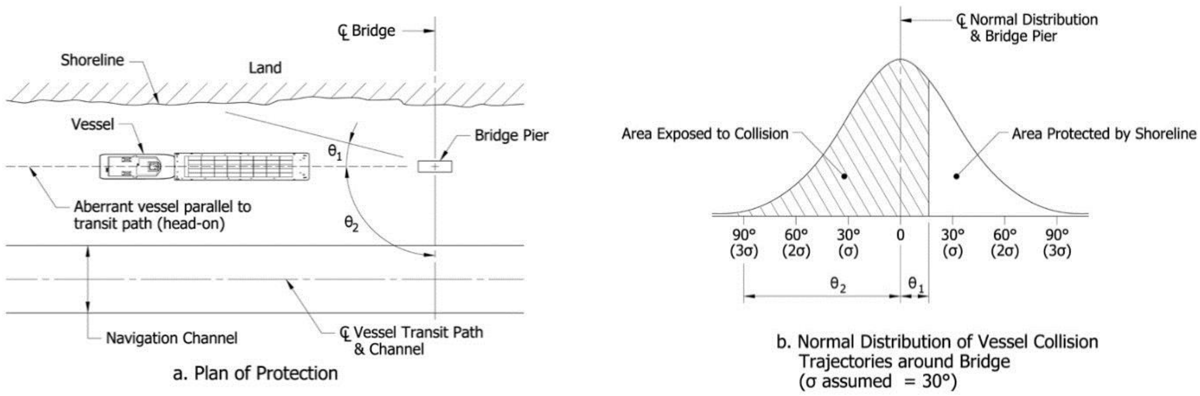
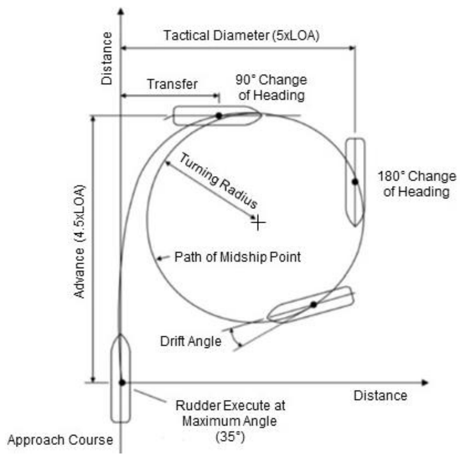


Figure 12: Protection Factor Illustration

In accordance with normal distribution properties, approximately 86% of all events occur within +/- 1σ, 95% within +/- 2σ, and 99% within +/- 3σ. Potential collision exposure angles can be developed based on the waterway/bridge geometry and vessel size. These angles can then be used in the normal distribution curve to estimate the probability of exposure to collision and the area protected by the feature under consideration. The protection provided is utilized to determine a PF value for use in the risk analysis. PF would be developed for each pier or span included in the risk analysis for both the upbound and downbound vessel directions, as applicable.



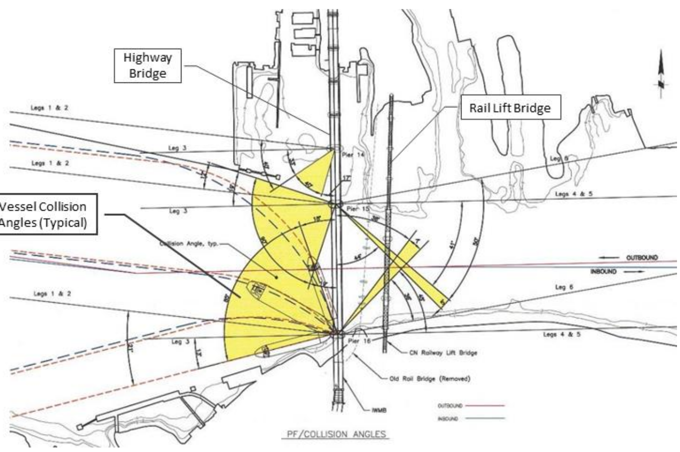


Figure 13: Aberrant Ship Turning Circles

Figure 14: Illustration of Collision Angles for Bridge Protection Factors (PF)

Physical protection features in the waterway near a bridge can be combined with the estimated movements of an aberrant vessel (Figure 13) to develop vessel collision angles used to estimate PF as illustrated in Figure 14. In Figure 14, vessels are transiting a narrow waterway and pass under both a highway bridge and an adjacent rail lift bridge.

2.7 Superstructure (Span) Collision

Vessel collision assessments are usually based on an evaluation of bridge piers in the waterway being hit by an aberrant vessel, however, for arch-shaped bridges an evaluation of potential superstructure collision must also be considered. For arch-shaped bridges the vertical clearance above water is reduced significantly between the edge of the channel and the piers supporting the arching superstructure. As shown in Figure 15, potential superstructure collision could occur between the mast of the vessel hitting the lower chord of the steel truss, the deckhouse of the vessel hitting the truss, or the top of the bow of the ship hitting the truss above water. Figure 15 also illustrates the potential pier collision scenario where the bulbous bow of an aberrant vessel hits the concrete pier supporting the bridge structure.

The location of the point of contact of an aberrant vessel mast, deckhouse or bow with the steel truss varies depending on the vessel size and draft (loaded or ballasted), geometry of the steel truss members, and the water elevation. Multiple water levels significantly complicates the superstructure risk analysis but should be considered in locations where tidal ranges are large. The vessel impact force also varies depending upon which part of the ship contacts the bridge component. Mast impact forces are smaller than deckhouse impacts, which are smaller than flared bow impacts, which are less than the full bow impact force on the pier (the largest impact force). In general the mast of an aberrant ship would contact the bottom chord of the truss before potential contact was made with the ship deckhouse (Figure 15).

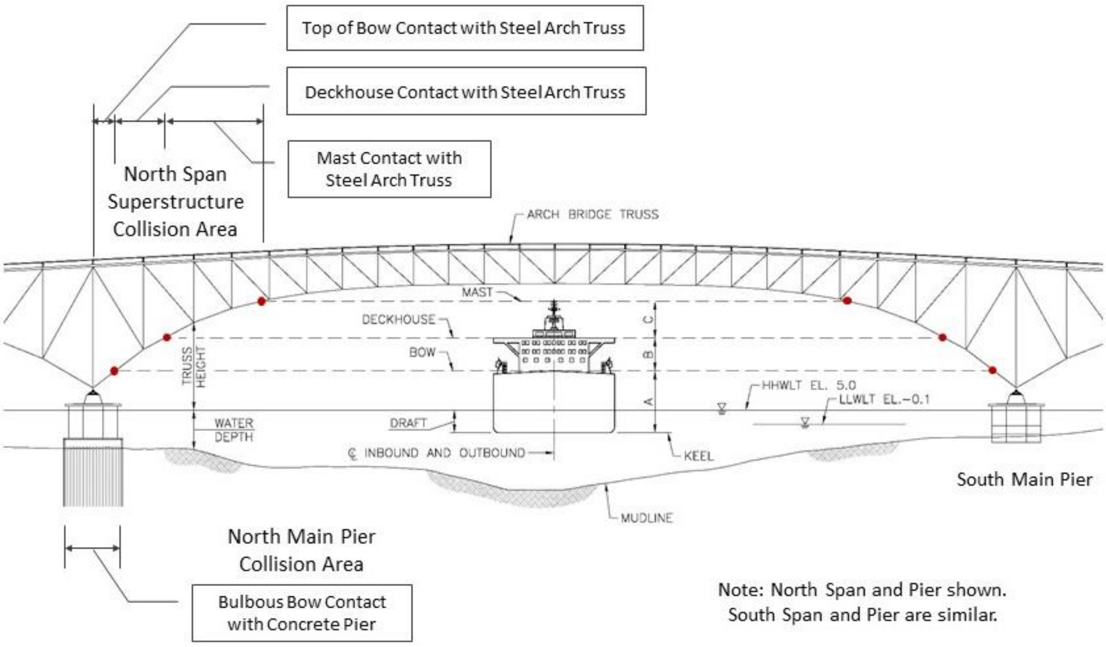


Figure 15: Superstructure (Span) Collision Geometry

3. ANALYSIS OF COMPLEX CHANNEL GEOMETRIES

As indicated throughout AASHTO 2009, the provisions represent an analysis simplification of a very complex problem. Procedures on how to evaluate typical ship/barge impacts are provided and illustrated and general principles are discussed, but it does not explicitly cover every conceivable situation that may be encountered. Therefore, it is left to bridge designers to use engineering judgment to apply the general analysis principles to model site-specific and sometimes complex bridge and navigation channel geometries.

An example of using AASHTO risk analysis principles to model a curved channel alignment near a bridge is shown in Figure 16. In this figure, the downbound vessel transit path is straight as ships/barges approach the main span of the bridge, but the upbound vessel transit path is highly curved due to existing waterway and navigational constraints. In order to model the curved vessel transit path, the upbound curve is broken into a series of six (6) 305m tangent sections ("legs") measured outward from the centerline of the bridge. The 1830m (6,000 feet) distance on each side of the bridge crossing represents approximately 1-nautical mile and was selected by AASHTO based on historical accident data (the Canadian Bridge Code 2014 uses 2,000m for the analysis limit). The selection of six (6) 305m legs was based on judgment and experience from similar risk analysis models. Another bridge designer might elect to use sixty (60) 30.5m legs to further refine the "mesh" used for analysis (all that would be required is additional computation and model development effort).

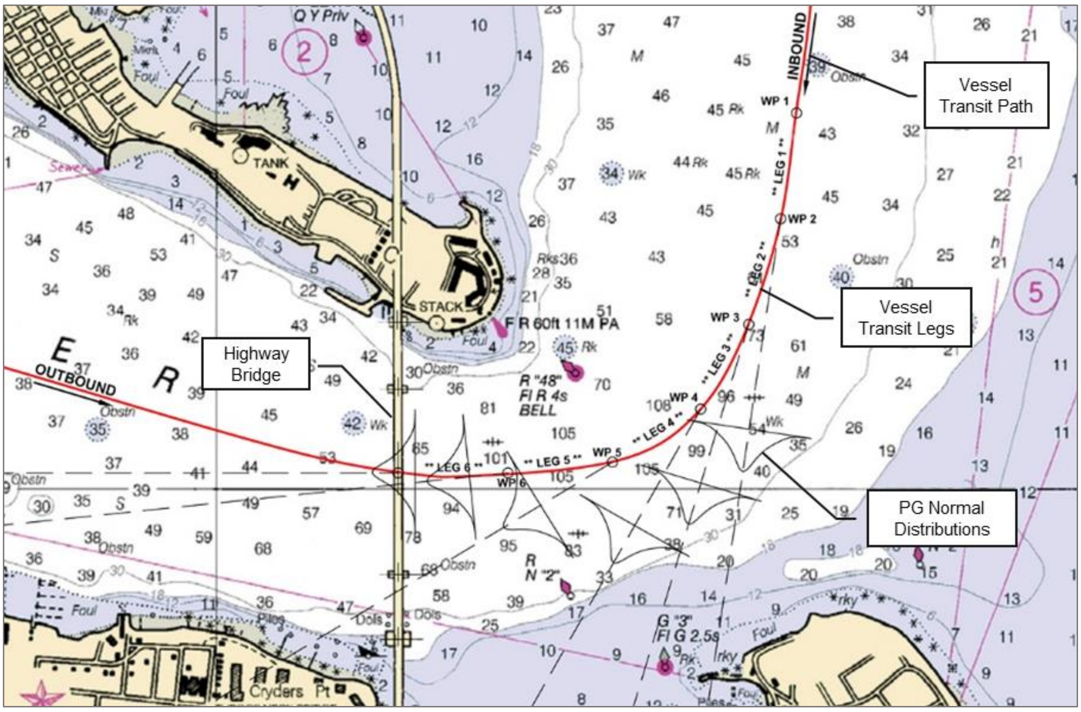


Figure 16: Illustration of Curved Channel Approach to Bridge

To conduct the risk analysis on the curved portion of the inbound transit path, each tangent section is computed as a "straight" section in the risk analysis and the 6 legs are added together to estimate the total inbound transit path AF. As shown in Figure 16, each leg has its own geometric probability (PG) distribution based on AASHTO's normal distribution centered on the tangent direction. The estimate of PG for each specific bridge pier or span component affected by an aberrant vessel is computed based on the bridge and waterway geometry associated with each leg and each vessel type. The legs are combined to estimate the risks due to inbound and outbound vessels, which are in turn combined to estimate the total bridge risk.

A probability of aberrancy (PA) must also be computed for each individual leg when conducting the risk analysis for the curved section. For the curved inbound transit path, the aberrancy base rate (BR) should be equally divided among the number of legs (so for the provided example, each inbound leg would have a base rate of BR/6). The base rates, which represent the minimum rates of accident frequency, are multiplied by correction factors for bridge location relative to bends in the waterway, currents acting parallel to vessel transit path, cross-currents acting perpendicular to vessel transit path, and the traffic density of vessels using the waterway. For each leg and its associated tangent geometry in the waterway, PA correction factors need to be determined, since the effect of currents and cross-currents can vary significantly.

It should be noted that the same aberrancy BR is used for both the inbound and outbound transit paths in the overall risk analysis. It is not divided by two (for each side) and then further divided by six for each tangent leg – that would be an incorrect application of the AASHTO requirements.

As seen in the example bridge in Figure 16, the PG associated with ships/barges that would become aberrant on Legs 1, 2 and 3 of the inbound transit path would not be headed in a direction that would potentially impact the bridge. They would instead run aground in the southern shallow waters of the river away from the bridge alignment. Inbound vessels becoming aberrant in Leg 4 would be on a principal path headed toward the bridge south main tower and anchor pier locations but away from the piers on the north side. Aberrant vessels in Legs 5 and 6 would be in a principal direction through the main navigation span of the bridge. As seen in the provided example, the AASHTO vessel collision provisions and principles can be adapted to model complex bridge and curved channel geometries.

4. WATER ELEVATIONS AND SCOUR

Available water depths are a key factor in determining which vessel could potentially strike bridge piers in a waterway. AASHTO 2009 states:

> "… As a minimum, the design water depth shall be computed from the bottom of the waterway to the annual mean high water level … In waterways where seasonal flooding represents a significant portion of the high-water activity, judgment must be used to establish the design water level."

The water level shown in AASHTO 2009 for ship and barge impact loads is noted as Mean High Water (MHW). It is certainly true that the terminology used in the current AASHTO requirements are based primarily on tidal waterways, with statements that "judgment" should be used where "seasonal flooding represents a significant portion of the high-water activity." This is an indirect Code reference to non-tidal waterways and represents a potential source of confusion or ambiguity on specifically how to apply the AASHTO collision requirements in a consistent and reasonable manner to non-tidal locations.

4.1 Maximum Impact Loads (Typical Vessel Transits)

Maximum impact loads due to aberrant vessels transiting the waterway at normal speeds should be developed differently between tidal and non-tidal waterways as discussed below.

Tidal Waterways: The water elevation used in determining the design depth for a vessel collision risk analysis is very important. AASHTO recommends using MHW for tidal areas and engineering judgment in non-tidal areas, such as inland rivers. In areas with tidal influence, there are typically 2 high tides per day. As a general simplified explanation, the average elevation of each high tide (each day) over the course of a year provides the MHW elevation. However, typically one of the daily high tides is higher than the other. Therefore, the average elevation of the highest daily tide (each day) over the course of a year provides the Mean Higher High Water (MHHW) elevation. Tides vary in elevation daily, weekly, monthly and seasonally due to the phases of the moon – usually so-called "spring tides" yield the highest tide elevations of the year.

Commercial merchant vessels transit a waterway throughout the year, so the selection of MHW as a design datum by AASHTO was based on a reasonably conservative water elevation that vessels would regularly experience while navigating under "normal" conditions. In general, vessels do not navigate through a waterway during severe storms and flood events but instead are tied-up at a dock or anchored until the high water and associated high current passes and "normal" conditions return. In fact, many inland navigable waterways have a flood level or "stage" established by the USCG and/or the U.S. Army Corps of Engineers (USACOE) that prohibits commercial navigation during an extreme high water event due to safety reasons.

Although the risk analysis is usually conducted using MHW, it is considered over-conservative in waterways with significant tidal fluctuations, such as the coastal areas of Canada where the tide variations exceed 5m on a daily basis. For locations where large tide variations exist, the tidal range is usually divided into 4 equal increments between MHW and Mean Low Water (MLW) levels and the risk analysis is conducted for each water level. This requires that the number of vessel transits (N) for each vessel category be allocated as appropriate to each water level. Although more accurate, there is a significant increase in the computational effort required when using multiple water elevations.

Non-Tidal Waterways: For non-tidal inland waterways, the use of MHW does not apply, but a similar thought process would be recommended in selecting a water elevation for the vessel collision risk analysis. A high water level that covers almost all "normal" conditions in which a commercial vessel may be navigating the waterway should be selected. Some U.S. state Departments of Transportation (DOTs) have adopted the "2% flowline" as the water datum for vessel collision analysis (this would effectively cover 98% of all water levels in the waterway). Flowlines are typically established for a specific waterway location using historical water-gage measurements obtained by federal and state agencies such as the USACOE, DOT, and National Oceanic and Atmospheric Administration (NOAA).

For the "normal" navigation scenario, the authors contend that use of a 2% flowline may be overly conservative when compared to the tidal waterways MHW limit. An exceedance curve developed for a typical tidal location shows that MHW is only surpassed approximately 10% of the time. Therefore, for a non-tidal location, a 10% flowline might be considered similar to the MHW level and more appropriate for use in the vessel collision risk analysis.

In summary, the primary goal for the "Maximum Impact" design scenario is to determine a reasonably conservative "typical/normal/average high water condition" under which vessels are routinely transiting the waterway, excluding water stages where navigation is shut down on the waterway. Water levels associated with extreme storm events should be excluded.

4.2 Minimum Impact Loads (Drifting Barge in a Storm Event)

Minimum Impact Loads due to a drifting barge in a storm event should be developed differently between tidal and non-tidal waterways as discussed below.

<u>Tidal Waterways</u>: Bridges and inland lock structures are routinely hit by vessels after they break loose from moorings during a severe storm event and are carried by winds and currents in the waterway. The vessels are usually empty barges that have broken loose and are drifting in the waterway. As a result, AASHTO has a minimum impact design requirement associated with an empty barge impacting any bridge pier located in water depths greater than 0.6m during a storm event. The barge is usually an empty 10.7m wide by 59.5m long hopper barge that is commonplace on the U.S. inland waterway system (but could be a different barge size depending on the specific waterway barge fleet).

The water level and water current for this situation should be based on the selected extreme storm event. AASHTO requires that all piers located in 0.6m of water (corresponds to the empty hopper barge draft) under the extreme storm event should be designed for the minimum vessel impact force.

For a new bridge, the 100-year design storm is typically selected for evaluation of the drifting barge scenario. On the U.S. East Coast, the 100-year storm is often related to an extreme hurricane event and hydrologic and hydraulic (H&H) models are used to determine both the water elevation and currents for bridge piers in the waterway. Depending on the depth and overall width of the waterway, different current speeds may exist over its width and should be considered for the various pier designs based on their locations.

<u>Non-Tidal Waterways</u>: For non-tidal inland waterways, a similar rationale and design process should be used to determine the extreme storm event and its associated water level and current for the drifting barge collision scenario. Historic records and H&H analysis can be used to establish a 100-year design event (or other alternative design year event as might be required).

5. COMBINATION OF VESSEL IMPACT LOADS AND SCOUR

Discussions concerning vessel collision extreme events also raise critical issues related to scour. The combination of vessel impact loads and scour are discussed in AASHTO 2009 for two design cases: 1) drifting barge during a storm event, and 2) aberrant vessels impacting bridge piers during normal operations while transiting the navigation channel. The following paragraphs are excerpts from AASHTO 2009:

> "Minimum impact loads associated with a drifting empty barge breaking loose from its moorings and hitting a bridge (potentially during storm and high water conditions). The drifting barge impact loads should be combined with one-half of the predicted long-term plus one-half of the predicted short-term scour. For this load case, long-term scour should be taken as the sum of the contraction scour portion of live bed scour and scour due to long-term channel degradation. Short-term scour should be taken as the short-term portion of the live bed scour associated with the 100-year storm/flood event."

> "Maximum impact loads associated with a ship or barge tow striking the bridge while transiting the navigation channel under typical waterway conditions (i.e., not during extreme storm events and high water conditions). The vessel impact loads should be combined with one-half of the predicted long-term scour."

> "Short-term scour includes contraction, local and live bed scour in which river or bay bottom material (sand, clay, gravel, etc.) is removed as a result of increased water velocities caused by flooding conditions in conjunction with the overall bridge geometry and substructure shape on the hydraulic conductivity of the site."

"In the U.S., historical data indicates that merchant ships and barge tows will not transit river and harbor areas during periods of high water and flood events which cause abnormal and dangerous water currents in the navigation channel. During such flood events, vessels will normally leave the harbor, tie-up at docks, or anchor in designated areas of the waterway. Following the passage of the flood stages of the waterway, and once currents return to normal levels, merchant shipping will recommence in the waterway. By that time it is anticipated that the short-term (live bed) scour areas near the bridge piers will have been significantly refilled by sediment transport mechanisms in the waterway. It is of interest to note that no records of any scour concerns are reported on any of the 31 major bridge collapses mentioned at the beginning of this report."

"At limited locations in the U.S., live bed scour conditions do not exist and instead, clearwater scour conditions may exist. In clearwater scour situations, up-river site conditions are such that there is virtually no particulate matter (soil, gravel, etc.) to transport; therefore, river bed material removed by local contraction scour is not replaced after flood level water velocities subside. Under this special condition, the full depth of scour should be used in the vessel collision analysis."

"Long-term scour includes aggradation and degradation scour and refers to scour across the entire waterway width. This is a permanent site condition with a magnitude (depth) that increases with time and is independent of the presence of a bridge or the structures geometry – this scour will occur regardless of the bridge. Long-term scour (if it is present at all) is usually a gradual deterioration of base support across the waterway."

In a typical bridge crossing, the long-term scour is usually a small value and is often not significant when evaluating the maximum impact load scenario. Of course each site has to be evaluated on its own merits before a specific design decision can be made.

6. VESSEL BOW CRUSHING AND BRIDGE PROTECTION

Based on the risk analysis results, a design vessel or a series of design vessels can be determined for each specific bridge pier location and/or superstructure element. Associated with each design vessel is an impact force and subsequent collision energy, as well as a general determination of the vessel bow geometry. An estimate of bow geometry is critical in determining if any portion of the ship/barge bow overhang can contact and cause damage to the bridge pier foundation or superstructure.

It is important for bridge designers to account for potential crushing of the vessel bow when determining bridge pier foundations (piles), footings, and general pier geometry. Consideration must also be given to not only the bow overhang above water, but also protrusions associated with a vessel bulbous bow below water. As shown in Figure 17 and Figure 18, after initial impact the vessel bow can be crushed a considerable distance and could possibly make contact with a vulnerable portion of the bridge pier, such as the tower (above water) or foundation piles (below water), causing catastrophic damage if not considered in the evaluation of protection measures.

Figure 17: Ship Bow Crushing

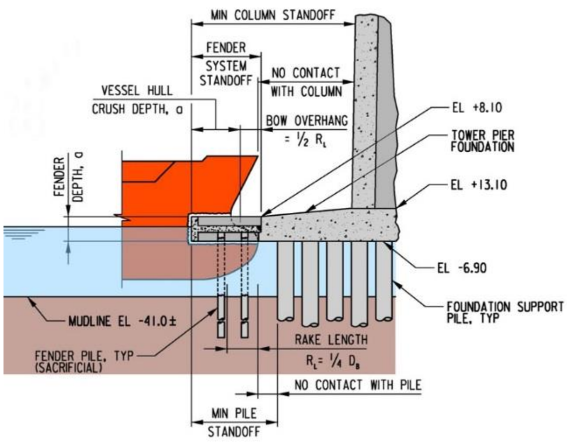


Figure 18: Ship Bow Crushing and Bridge Pier Geometry

In Figure 17, a ship crashed into a container terminal wharf, which effectively sliced through the bow of the ship for a relatively significant distance (until the collision energy was absorbed). The underwater bulbous bow portion of the ship also destroyed numerous piling that supported the wharf structure. The wharf structure and piling where the ship made contact had to be repaired/replaced.

As shown in Figure 18, bridge pier design should consider crushing of the vessel bow under impact conditions to determine the appropriate stand-off distance required for both underwater (piling) and above water contact with bridge pier elements. The amount of bow crushing can be calculated using AASHTO procedures based on the vessel impact force and energy and the geometry and strength of the bridge pier structure. In general, the vessel bow will crush until the impact energy is absorbed, assuming that the pier structure is sufficiently strong to withstand the impact forces both locally and globally. For major bridge projects sophisticated explicit solver finite element models (FEM) of both the design vessel and the bridge piers are usually developed for dynamic impact analysis as part of the design process.

7. CONCLUSIONS

Vulnerability of highway and railroad bridges to potential catastrophic collapse due to ship and barge collisions can be evaluated using AASHTO provisions for both relatively simple and complex bridge and navigable waterway geometries.

This paper illustrated application of the AASHTO vessel collision principles for curved navigation channels near bridges; selection of the appropriate water depth and scour for use in the risk analysis for the evaluation of both tidal and non-tidal waterways; development of protection factors (PF) for use in the risk analysis; adjustments to probability of aberrancy (PA) for modern navigation practices; modifications to the geometric probability (PG) for tethered tug assistance; and highlighted the importance of considering vessel bow crushing when evaluating the consequences of potential local contact between an aberrant ship/barge bow with a bridge pier.

It should be noted that the discussion and recommendations on the application of the AASHTO procedures in this paper represent the personal opinions of the authors only and should not in any way be considered an official position of AASHTO or any other organization or company.

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