STRUCTURAL RELIABILITY ANALYSIS FOR VESSEL IMPACT ON BRIDGES

by

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DEDICATION

To my Family.

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ABSTRACT

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The collapse of the Queen Isabella Causeway in 2001 due to a vessel collision was an alarming message to the state of Texas that vessel impact on bridges is a serious issue and may need to be considered for all bridges that span waterways. The Texas Department of Transportation funded this research project that was aimed at examining in detail the AASHTO LRFD code provisions for vessel impact on bridges. The goals of the present study are to develop a stand-alone computer program that utilizes information on waterways, vessels, traffic, and bridges in a probabilistic analysis that estimates the annual frequency of collapse.

According to today's code provisions for vessel impact on bridges, a bridge is required to have a specific minimum return period associated with collapse depending on its importance classification. A user-friendly stand-alone computer program, VIOB, is developed to make it possible to carry out the required calculations that lead to estimates of the return period.

Given information related to the bridge and pier geometry, the waterway, and the vessel traffic at a given mile marker of a waterway where the bridge is located, VIOB produces an in-depth report detailing all the calculations. This report provides information on the analysis performed and also includes summaries that allow the user to determine sources of vulnerability for the bridge. Such information is useful in improving a bridge design when, for example, code specifications are not met. VIOB integrates databases with analysis capabilities and makes it possible to carry out calculations related to an important problem – the safety of bridges against vessel impact.

Table of Contents

List of Tables

List of Figures

CHAPTER 1
Introduction

1.1 BACKGROUND

The Queen Isabella Causeway allows vehicles to drive from Port Isabella, Texas along Park Road 100 over the Gulf Intercoastal Waterway to South Padre Island. On September 15, 2001 a four-barge tow collided with the Queen Isabella Causeway triggering a collapse of Bent 32. The collapse can be seen in Figure 1-1. The catastrophe left a gaping 160-foot fissure in the bridge and caused the deaths of eight people as their cars plunged 87 feet into the water below (Schwartz, 2001; Texas Civil Engineer, 2004).

Figure 1-1: The Queen Isabella Causeway Collapses in September 2001 (Source: Calzada).

At the time of the accident, the Queen Isabella Causeway was the only means of transportation for visitors to and from South Padre Island. The destruction of this bridge, shown in Figure 1-2, effectively stranded thousands of people on the island until ferries could be brought in to transport them to the mainland. Given the importance of this bridge to the surrounding communities, the tragedy due to the loss of life was exacerbated by the economic crippling of an entire region.

Figure 1-2: The Collapsed Portion of the Queen Isabella Causeway (Source: South Texas Business Directory).

When the captain and crew of the barge tow were questioned about the incident, it was determined that neither drugs nor alcohol were involved in the accident; however, the barge tow was several hundred feet off course when it slammed into the Queen Isabella Causeway. One possible explanation that has been suggested is that there might have been some particularly high currents in the curved channel leading up to the bridge at the time of the accident that the captain of the barge tow was unaware of (Schwartz, 2001).

Vessel collisions are not unique to Texas. Months after the Queen Isabella Causeway disaster, Oklahoma experienced a similar bridge collapse. On May 27, 2002 a barge captain blacked out as his barge tow was approaching Interstate 40 where it crosses over the Arkansas River in Webbers Falls, Oklahoma. The collision caused 600 feet of the bridge to collapse (See Figure 1-3), killing fourteen people when their vehicles drove off the collapsed bridge (National Transportation Safety Board, 2004).

Figure 1-3: Bridge in Webbers Falls Oklahoma Collapses Due to Vessel Collision (Source: The Anniston Star).

While the Webbers Falls and Queen Isabella Causeway vessel collisions were fairly recent, the history of vessel collisions with bridges in the United States is quite extensive. Possibly the largest bridge collapse due to vessel impact in the U.S. occurred in 1980 in Tampa Bay where a 1400-foot span of the Sunshine Skyway Bridge was destroyed when a ship collided into one of the main piers killing 35 people. In 1993, a barge tow collided with the Judge William Seeber Bridge in New Orleans killing three people.

Vessel collisions with bridge piers have occurred in the past and they will likely continue to occur in the future. According to Frandsen (1983), the annual rate of catastrophic collisions during the period 1960-1970 was 0.5 bridges per year. However, that number tripled to 1.5 bridges per year during the period 1971-1982. This increased number of bridge failures over time resulted due to an increase in the number of bridges over navigable waterways as well as an increased volume of vessels using those waterways (AASHTO, 1991).

The recent Queen Isabella Causeway bridge collapse and other vessel collisions on bridges motivated the present research study supported by the Texas Department of Transportation (TxDOT) which aims to evaluate bridges spanning waterways in the state of Texas for safety against vessel collisions.

Having experienced the horrific disaster that occurred due to the Queen Isabella Causeway collapse, TxDOT decided to analyze each of the state's bridges that span waterways to determine if rehabilitation might be needed to prevent a similar accident. Using available software that can assess the likelihood of a bridge collapse due to vessel collisions, TxDOT performed the appropriate AASHTO calculations which also helped identify bridges that require attention. A shortcoming of the analyses that were carried out was that the data especially on vessel traffic and waterways were not generally available.

This thesis is part of a research study that is comprised of three separate tasks: structural reliability analysis, bridge ultimate strength models, and finite element modeling to assess impact forces. In addition, a comprehensive database development effort is an integral part of this research project. The parts of the project will be integrated together to help identify Texas bridges that might be at risk of failure due to vessel collision.

1.1.1 Bridge ultimate strength models

In order to accurately assess the vulnerability of a bridge against vessel impacts, it is necessary to determine the strength of exposed bridge piers. By taking into account such factors as the superstructure stiffness, soil stiffness, vessel force, and pier geometry, models are being developed (Henderson, 2005) to determine the ultimate lateral strength of a bridge pier. Different structural analysis computer programs such as ANSYS and SAP2000 are being used to perform nonlinear static pushover analyses to determine the ultimate strength of a pier.

1.1.2 Finite element modeling to assess impact forces

Using LS-DYNA, a finite element analysis program, models are being developed (Cryer, 2005) to determine the characteristics of the force transferred from a vessel to a pier during a collision. Important variables include the vessel speed, current velocity, pier stiffness, vessel hull stiffness, and angle of impact. Taking into consideration these variables, a model is being developed to provide descriptions of the impact force for the reliability study.

1.1.3 Data Collection

Because data on waterway characteristics and vessel traffic on Texas waterways are not easily available, a database is being developed as part of this research study. Using information from sources such as the Army Corps of Engineers and commercial towing companies, vessel traffic and channel data are being assembled at various mile markers on Texas waterways. The data include information regarding channel profile, channel currents, vessel traffic, and vessel geometry. These data are essential in assessing the return period for bridge collapse due to vessel impact.

1.1.4 Structural Reliability Analysis

Using models developed for vessel impact forces and for ultimate strength of piers along with data on vessel traffic and on the channels, a probabilistic framework is developed to estimate the return period associated with bridge collapse due to vessel impacts. Calculations also involve the use of databases developed along with formulations for estimating the probability of aberrant vessels, consideration of the channel geometry, and the vessel traffic. Estimates of the return period help transportation agencies identify bridges that might be vulnerable to collisions and are useful in prioritizing resources for retrofitting of at-risk bridges that span waterways.

1.2 SCOPE OF THESIS

There are many different factors that influence vessel impact analysis for bridges including the bridge geometry and structural properties, channel characteristics, and vessel traffic data. This thesis focuses on the structural reliability analysis calculations which are integrated into a stand-alone analysis program that makes use of databases and models to evaluate bridge against vessel impact. The entire numerical framework for estimating return periods for bridge collapse due to vessel impact involving various models as well as Texas-specific databases has been conveniently incorporated in a user-friendly software program, VIOB, which is developed as part of this study. This software program allows the user to complete detailed calculations of the type needed when following the AASHTO LRFD specifications (AASHTO, 2004). The ease of use of this software is a major improvement over previously existing computational tools for such analyses.

1.3 Organization of Thesis

This thesis is organized in the same way that the research itself progressed. First, a literature review describing past research efforts is presented in Chapter 2. This is followed in Chapter 3 by a detailed description of the AASHTO LRFD methodology currently in use when evaluating bridges for vessel impact loads. Next, some changes to the AASHTO methods that we propose for the reliability analysis based on our understanding of vessel impact forces and bridge pier ultimate strength models are described in Chapter 4. A set of example calculations are included in Chapter 5. Building on the example calculations, Chapter 6 compares results for different bridges. A presentation of VIOB, the computer software developed for this research is outlined in Chapter 7. Finally, some general conclusions arising from this research are included in Chapter 8.

CHAPTER 2

Literature Review

2.1 Previous Vessel Impact Studies

Consideration for the design of bridges against vessel impact is important in many countries around the world. Land-locked countries must be concerned with vessel traffic in rivers, channels and lakes, while countries by the ocean must account for vessel traffic entering and leaving its ports. Vessels have been known to collide with other vessels, with bridge piers, and with other obstacles. Countries like the United States, Japan, and Germany have, over the years, carried out numerous research studies dealing with vessel impact on bridges and other obstacles.

In Japan, Fuji and Shiobara (1978) reported on tests representing ship-to-ship collisions to determine the annual economic losses occurring in Tokyo Bay. Their studies related the probability of collision between two vessels at sea and the associated rate of damage caused. Due to a lack of vessel-to-pier collision data at the time of the writing of the 1991 AASHTO Guide Specification (AASHTO, 1991), studies of ship-ship collisions including the one by Fuji and Shiobara (1978) were modified to apply to vessel-pier collisions.

The commentary in both the AASHTO LRFD Specifications (AASHTO, 2004) and the earlier 1991 Guide Specification (AASHTO, 1991) refers to two sets of experiments conducted in Europe that were used as a basis for establishing critical relationships provided in the Specifications for computing vessel damage and impact forces. For ships, these experiments were largely based on the work of Woisin, conducted in Germany in the late 1960s to the mid 1970s (Woisin, 1970, 1971, 1976). Similarly, for barges, the expressions in the two AASHTO documents provided for vessel damage and collision force were based on the experimental work of Meir-Dornberg, published in German in 1983 (Meir-Dornberg, 1983).

Inland waterways in Germany have bridges that are very old and were not originally designed for vessel impact. A recent study (Proske et al., 2003) discusses an approach for strengthening of such old bridges. Probabilistic analysis techniques are used to correlate bridge damage to the number of ship impacts for different bridge structures.

As far as experience with vessel impact studies in the United States is concerned, all states have bridges crossing waterways and hence, vessel collision is a problem in every state, not simply coastal states. While national codes have been established to design against vessel collisions, research has been mostly performed in states which are at greatest risk. Florida and Louisiana have led vessel collision research efforts in the U.S. but other states such as New Jersey and Kentucky have also influenced code development. Texas, too, has undertaken its own research into vessel collision design.

The state of Louisiana and the Federal Highway Administration introduced one of the first comprehensive code criteria for vessel impact (Modjeski and Masters Consulting Engineers, 1984). These criteria describe in detail how to perform a vessel collision probabilistic analysis based on bridge, vessel, and channel data. The model uses a dynamic analysis to determine vessel forces and also provides a simplified approach for design. This model was one of the primary sources that led to the development of the 1991 AASHTO Guide Specifications (AASHTO, 1991).

In the state of Florida, a significant amount of research has been done on the topic of vessel impact on bridges. The University of Florida and the Florida

Department of Transportation have recently performed extensive tests relating to vessel impact on bridges (Consolazio et al., 2005). In the area of probabilistic analysis for the return period of bridge collapse due to vessel impact, a Mathcad spreadsheet that could be linked to a vessel traffic database was developed to enable estimation of the annual frequency of collapse of susceptible bridges in the state of Florida (Florida Department of Transportation, 2000).

The state of New Jersey has also dealt with vessel collision situations in practice. For example, when Parsons Brinckerhoff was involved in the design of the Ocean City – Longport Bridge in the state, vessel collision forces controlled the design of several piers. It was found to be most economical to use longer spans in the center portion of the bridge and the use of a fender system had a significant reduction in the annual frequency of collapse of the bridge (Rue et al., 2002).

In the state of Kentucky, the use of various types of data with Method II as given in the AASHTO Guide Specification is demonstrated by Whitney et al. (1996) for a cable-stayed bridge in the state.

2.2 CHANGES IN THE DESIGN CODE

While research into vessel impact design had been performed for many years around the world, vessel impact design did not seriously begin in the United States until 1980 when the Sunshine Skyway Bridge, in Tampa Bay, Florida, collapsed due to a ship collision (see Figure 2-1). This catastrophic event forced researchers and officials to take a closer look at the frequency of vessel collisions and methods to prevent further accidents from occurring.

Figure 2-1: 1980 Sunshine Skyway Bridge Collapse (Source: Time Magazine).

2.2.1 The 1991 AASHTO Guide Specification and Commentary for Vessel Collision Design of Highway Bridges

The first attempts by AASHTO to formally address the design of bridges for vessel collision forces were made in 1991. Following the Sunshine Skyway Bridge disaster, research into vessel collision was thought to be necessary. AASHTO examined the results from several research projects in other countries (see, for example, Fuji and Shiobara, 1978; Woisin, 1970, 1971, 1976; and Meir-Dornberg, 1983) and in the United States (e.g., by Modjeski and Masters, 1984) and developed their first guide specifications (AASHTO, 1991). These specifications, while not required for bridge design, include a large commentary component and propose guidelines for determining vessel impact loads and a procedure for designing a protective bridge barrier. The guide specifications also attempt to create a preliminary vessel database that encompasses the most common types of vessels in use on waterways in the U.S.

2.2.2 The 2004 AASHTO LRFD Bridge Design Specifications

Starting in 2004, vessel collision was formally incorporated into the primary AASHTO LRFD design code for bridges (AASHTO, 2004). The guidelines here were adapted from the 1991 AASHTO Guide Specification with minor modifications made to streamline the design process and keep it consistent with the rest of the LRFD code. Also, only Method II from the 1991 Guide Specification was retained in the 2004 AASHTO LRFD code. This method is the optimal method of vessel collision design in terms of complexity and is similar in principle with the overall LRFD probabilistic design philosophy. These AASHTO 2004 LRFD guide lines for vessel collision are discussed in further detail in Chapter 3.

CHAPTER 3

The AASHTO Specifications for Vessel Impact on Bridges

3.1 IMPLEMENTATION OF AASHTO GUIDE SPECIFICATION

Developed from the *AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges* (AASHTO, 1991), the AASHTO LRFD code Section 3.14 outlines a procedure for estimating a bridge's likelihood of collapse given that a vessel collides with it.

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

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

3.1.1 Annual Frequency of Collapse

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

$$AF_{ij} = (N_i)(PA_{ij})(PG_{ij})(PC_{ij}) \tag{3.1}$$

where:

AF_{ij} = Annual frequency of collapse of pier *j* caused by vessel type *i*,

N_i = Annual number of vessel type *i* (a vessel must pass all piers),

PA_{ij} = Probability of aberrancy of vessel type *i* with respect to pier *j*,

PG_{ij} = Geometric probability associated with vessel type *i* and pier *j*,

PC_{ij} = Probability of collapse of pier *j* due to vessel type *i*.

Equation 3.1 suggests that the annual frequency of collapse is based on a number of different probabilities. In sequence we need to know the probability that a vessel becomes aberrant; then, the probability that a vessel will strike the bridge given that it becomes aberrant; and finally the probability that the bridge will collapse given that a vessel is aberrant and strikes the bridge.

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

$$AF_{Total} = \sum_{i=1}^{NV} \sum_{j=1}^{NP} AF_{ij} \tag{3.2}$$

where:

AF_{Total} = Annual frequency of collapse of the bridge,

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

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

The sequence of computations is such that the annual frequency of collapse is determined for each pier and the sum of these frequencies for all piers provides the overall annual frequency of collapse of the bridge. For a bridge classified as "critical," the annual frequency of collapse must be not greater than 0.0001, or its return period must be not shorter than 10,000 years. The required annual frequency of collapse for a bridge designated as "regular" must be no larger than 0.001 corresponding to a return period of 1,000 years. In terms of these acceptable levels, we have:

$$AF_{Total} < AF_{Acp} \tag{3.3}$$

where:

AF_{Total} = Annual frequency of collapse of the bridge,

AF_{Acp} = Acceptable annual frequency of collapse of the bridge.

3.1.2 Probability of Aberrancy (PA)

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

$$PA = (BR)(R_B)(R_C)(R_{XC})(R_D) \tag{3.4}$$

where:

PA = Probability of aberrancy,

BR = Aberrancy base rate,

R_B = Correction factor for bridge location,

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

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

R_D = Correction factor for vessel traffic density.

3.1.2.1 Aberrancy Base Rate

From Equation 3.4, is can be seen that probability of aberrancy is calculated by starting with a base rate and then modifying it by four different factors. The four correction factors adjust for bridge location, parallel current, perpendicular current, and traffic density. Each of the five variables that influence probability of aberrancy is based on historical data for the waterway.

The aberrancy base rate is the fraction of vessels that become aberrant. Ships are less likely to become aberrant than barges; therefore, the base rate for a ship is 0.00006 as opposed to 0.00012 for barges.

3.1.2.2 Correction for Bridge Location

A correction factor for bridge location is necessary to adjust for the different types of channel geometry in the vicinity of the bridge. Different turn regions exist in any channel and the sharper the turn angle the more difficult it becomes for the vessel operator to keep the vessel on course. The AASHTO LRFD code distinguishes channel regions into three types: straight, transition, and turn/bend.

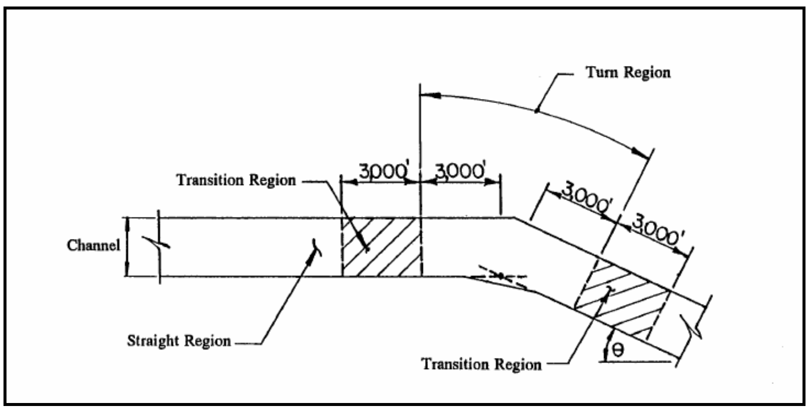


Figure 3-1: Channel turn region (from AASHTO LRFD Figure 3.14.5.2.3-1a)

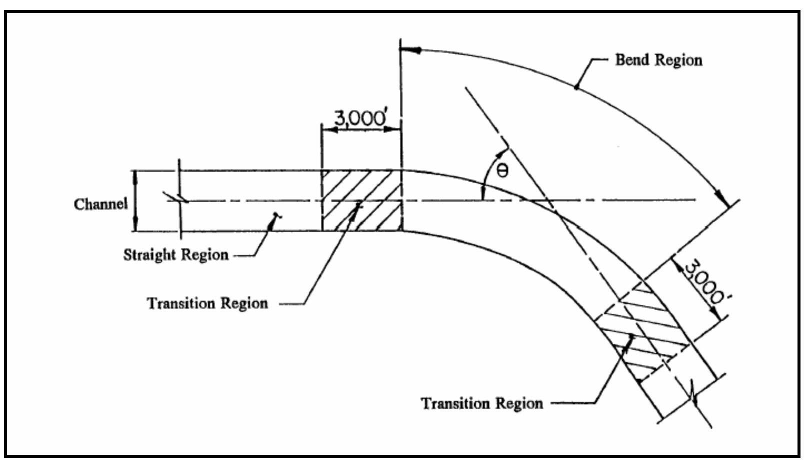


Figure 3-2: Channel bend region (from AASHTO LRFD Figure 3.14.5.2.3-1b)

A straight region is the simplest; here, a vessel has a clear straight path underneath the bridge. A turn or bend region, shown in Figure 3-2, would be a place where the bridge crosses the channel while the channel is changing directions (See Figure 3-1 for an illustration of a turn region and Figure 3-2 for a channel bend region.). The transition region is a 3000-foot long region before and after the turn or bend region. If a bridge is located in a transition region, it is more difficult for a vessel to navigate the channel than with a straight channel, but not quite as challenging as it would be in a turn or bend region. The difference between a turn region and a bend region is only that a turn region has a sharp-angled change in channel geometry while a bend region has a smoother curved-angle change. However, both turn and bend regions are handled the same way in the AASHTO LRFD code.

For straight regions:

$$R_B = 1.0 \tag{3.5}$$

For transition regions:

$$R_B = \left(1 + \frac{\theta}{90^\circ}\right) \tag{3.6}$$

For turn/bend regions:

$$R_B = \left(1 + \frac{\theta}{45^\circ}\right) \tag{3.7}$$

where:

R_B = Correction factor for bridge location,

θ = Angle of turn or bend (°) as shown in Figure 3-1 and Figure 3-2.

3.1.2.3 Correction for Current

In the computation of the probability of aberrancy, these are the next two corrections that account for the velocity of the water current. It is necessary to correct for both the current flow parallel to the vessel traffic and the current flow perpendicular to the vessel traffic. As the current velocity increases, it becomes more difficult to maintain the vessel's heading. Currents in the two directions do not have an equal effect on vessel aberrancy. The correction factor for the cross current has ten times the influence of that for parallel currents.

$$R_C = \left(1 + \frac{V_C}{10}\right) \tag{3.8}$$

where:

R_C = Correction factor for current parallel to the direction of vessel traffic,

V_C = Velocity of current parallel to the direction of vessel traffic (knots).

$$R_{XC} = \left(1 + V_{XC}\right) \tag{3.9}$$

where:

R_{XC} = Correction factor for current perpendicular to the direction vessel traffic,

V_{XC} = Velocity of current perpendicular to the direction of vessel traffic (knots).

3.1.2.4 Correction Factor for Vessel Traffic Density

The final correction factor in the computation of probability of aberrancy is due to vessel traffic density in the waterway. Higher traffic density equates to an increased probability that a vessel will become aberrant. The AASHTO LRFD code categorizes traffic density very broadly into low, medium, and high levels.

Low traffic density:

$$R_D = 1.0 \tag{3.10}$$

Average traffic density:

$$R_D = 1.3 \tag{3.11}$$

High traffic density:

$$R_D = 1.6 \tag{3.12}$$

where:

R_D = Correction factor for traffic density.

The combination of the aberrancy base rate and the four correction factors described above yields an estimate for the probability of aberrancy. In general, a higher probability of aberrancy can directly lead to a higher annual frequency of collapse or a lower return period.

3.1.2.5 Limitations

The equations for probability of aberrancy in the AASHTO LRFD code were developed in the AASHTO Guide Specifications (AASHTO, 1991). Data from bridges around the world were collected and led to estimates base rates of aberrancy for ships and barges. The base rate for barges was found to be two to three times higher than that for ships. The limitations associated with probability of aberrancy stem mostly from the quality and quantity of available data and the lack of ability to make appropriate site-specific modifications. The four correction factors used in the AASHTO LRFD code are just a few of the many different variables that determine whether a vessel becomes aberrant. Other variables such as wind, visibility conditions, navigation aids, and human error can have a strong influence on the probability of aberrancy but they were not directly included in the AASHTO LRFD code as they were considered to difficult to quantify. Such factors were indirectly accounted for in the base rate; however, if any one of these is particularly significant at a given waterway and bridge location, its influence on the results would not be indicated. Human error which accounts for 60 to 85 percent of all aberrant vessels is the most difficult variable to quantify.

It is expected that advances in technology such as computer-guided vessels and warning technologies would be able to vastly improve the base rate for vessels. Technological improvements should also decrease the influence of the four correction factors that were accounted for.

3.1.3 Geometric Probability (PG)

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

The AASHTO LRFD code uses a normal distribution to account for geometric probability. The standard deviation is taken as the overall length of the vessel (LOA). The probability density function for a normally distributed random variable is as follow:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{3.13}$$

where:

σ = Standard deviation (For PG, σ = LOA),

μ = Mean (For PG, $\mu = 0$).

To determine the geometric probability, two points are plotted on the x-axis. The variable x refers to the possible location of the center of a vessel relative to the centerline of a channel. This can be viewed in Figure 3-3.

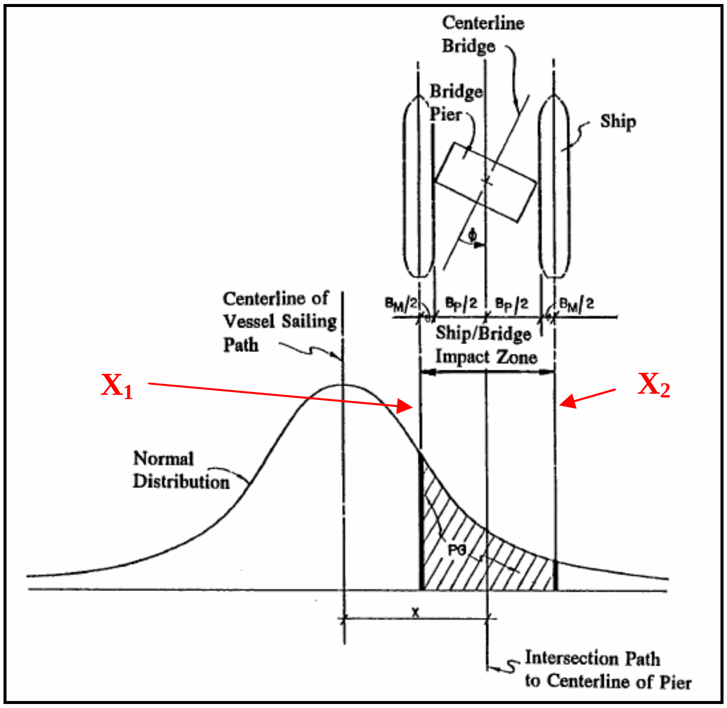


Figure 3-3: Normal distribution curve for geometric probability. (AASHTO LRFD code Figure 3.14.5.3-1)

The geometric probability represents the probability that the vessel lies between X_1 and X_2 (See Figure 3-3).

$$X_1 = \frac{x - \frac{B_P + B_M}{2}}{LOA} \tag{3.14}$$

$$X_2 = \frac{x + \frac{B_P + B_M}{2}}{LOA} \tag{3.15}$$

where:

X_1 = Lower bound for location of vessel that can collide with the pier,

X_2 = Upper bound for location of vessel that can collide with the pier,

x = Distance from centerline of navigable channel to centerline of pier,

B_P = Width of pier,

B_M = Width of vessel,

LOA = Length overall of vessel.

The geometric probability, PG, is the area under the normal distribution curve between X_2 and X_1:

$$PG = \Phi(X_2) - \Phi(X_1) \tag{3.16}$$

where:

PG = Geometric Probability,

$\Phi(X_i)$ = Standard normal cumulative distribution function evaluated at x_i,

X_1 = Lower bound probability,

X_2 = Upper bound probability.

It has been shown in various studies, most notably in the development of the AASHTO Guide specification (AASHTO, 1991), that piers outside of 3LOA from the navigable channel centerline are unlikely to be struck by a vessel.

Therefore, any piers more than 3LOA away from the centerline of the navigable channel are not considered in the computation of PG.

3.1.3.1 Limitations

The limitations of estimating the geometric probability of geometry are due to lack of data on barge collisions. In developing a model for estimating geometric probability, a wide variety of ship data was available, however very few data referring to barge collisions exist. The AASHTO LRFD code recommends that the same standard deviation of LOA be used for barge groups, even though there is no statistical evidence to support that value.

3.1.4 Probability of Collapse (PC)

Given that vessel has gone aberrant and has struck a pier, it is then necessary to estimate the probability that the bridge will collapse. Several variables including vessel size, type, configuration, speed, direction of impact, and mass influence the probability of collapse. The stiffness of the bridge pier and the nature of bridge superstructure also influence the probability of bridge collapse.

The AASHTO LRFD code Section 3.14.5.4 which addresses probability of collapse was developed by Cowiconsult (1987) based of studies performed by Fujii and Shiobara (1978) using Japanese historical damage data on vessels colliding at sea (AASHTO LRFD C3.14.5.4). The ratio of ultimate lateral resistance to the vessel impact force is computed in order to estimate the probability of collapse. The LRFD equations governing probability of collapse are as follow:

If $0.0 \le H/P < 0.1$:

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right) \tag{3.17}$$

If $0.1 \le H/P < 1.0$:

$$PC = \frac{1}{9}\left(1 - \frac{H}{P}\right) \tag{3.18}$$

If $H/P \ge 1.0$:

$$PC = 0.0 \tag{3.19}$$

where:

PC = Probability of collapse,

H = Ultimate lateral resistance of pier (kips),

P = Vessel impact force (kips).

The ultimate strength of a single pier is typically conservatively assumed to be the ultimate strength of the entire bridge. A plot of equations 3.17 to 3.19 provides a better picture of how the probability of collapse is computed. As seen in Figure 3-4, working from right to left, if the bridge element strength, H, is greater than the vessel impact force, P, there is a zero probability that the bridge will collapse. As the H/P ratio increases, the probability of collapse remains low until the vessel impact force becomes greater than one-tenth the ultimate lateral pier strength. From then on, small reductions in the H/P ratio cause the probability of collapse increase quite sharply. Eventually, the probability of collapse reaches 1.0 where the vessel impact force exceeds the ultimate lateral pier strength.

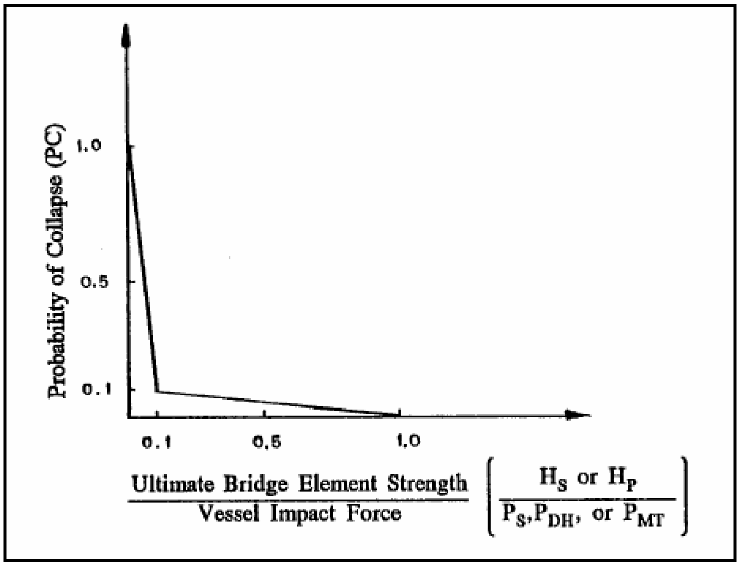


Figure 3-4: Probability of collapse distribution. (from AASHTO LRFD code Figure C3.14.5.4-1)

3.1.4.1 Ultimate Lateral Pier Strength

In order to determine the ultimate lateral strength of each pier, a separate analysis must be done outside of the AASHTO LRFD code calculation for annual frequency of collapse due to vessel impact. Either a nonlinear static pushover analysis or a nonlinear dynamic analysis may be employed for this purpose.

3.1.4.2 Vessel Impact Force

The impact force of a vessel on a pier is based on a number of different variables including vessel type, vessel impact velocity, strength and stiffness of the pier, and the angle of collision. The kinetic energy of the moving vessel must be computed to determine how much force is transferred from the vessel to the pier. In order to calculate kinetic energy, the impact velocity of the vessel must be estimated.

Vessel velocity is difficult to establish because the velocity of the vessel must be combined with the velocity of the current. In any given waterway, the water speed is not constant at all locations across the channel. In addition, it is necessary that the velocity of the vessel be considered when it has become aberrant. Often a vessel that has strayed considerably off course will no longer maintain its original speed but will rather be moving with the channel current velocity.

Based on various studies performed in the past, the AASHTO LRFD code Section 3.14.6 proposes a means for determination of the vessel velocity. A linear interpolation is used to represent the variation in velocity from the centerline of the waterway to the edges of the channel. Figure 3-5 shows the velocity distribution used in the code.

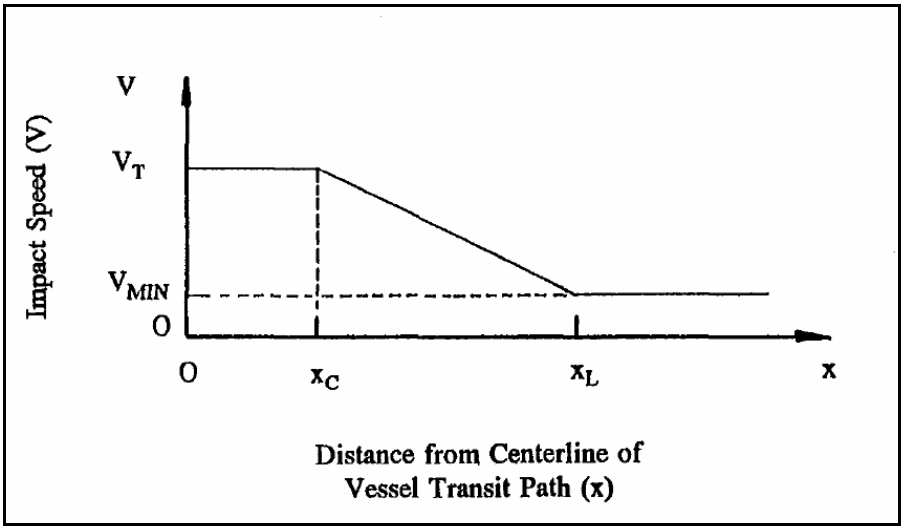


Figure 3-5: Variation of design collision velocity with distance from navigable channel centerline. (from AASHTO LRFD code Figure 3.14.6-1)

where:

V = Design impact velocity,

V_T = Typical vessel transit velocity (under normal environmental conditions),

V_{MIN} = Minimum design impact velocity (not less than the yearly mean current velocity),

x = Distance to face of pier from centerline of channel,

X_C = Distance to edge of channel,

X_L = Distance equal to three times the overall length of the vessel.

Vessel velocity should be determined using typical current velocities and taking into account wind and other external forces. The velocity of a vessel may be different for upbound and downbound vessels. This velocity can be accounted for by running two separate calculations, one for each direction. It would seem logical to add the velocities of the vessel and channel current velocity for downbound and subtract them for upbound vessels; however this is not done. No distinction is made regarding vessel motion direction in the AASHTO LRFD code. This is because a minimum velocity, V_{MIN}, is required, as seen in Figure 3-5, and it must be greater than the yearly mean current velocity. In other words, a negative velocity that might result from a large current opposite to the vessel traffic direction is not permitted in the AASHTO LRFD code.

Once the velocity of the vessel in known, the kinetic energy of the vessel can be determined. Kinetic energy is based on a number of parameters including vessel displacement tonnage, impact velocity, and a hydrodynamic mass coefficient that accounts for the influence of the surrounding water upon the moving vessel. This is detailed in AASHTO LRFD code Section 3.14.7. The kinetic energy of a moving vessel is computed as follows:

$$KE = \frac{C_H W V^2}{29.2} \tag{3.20}$$

where:

KE = Vessel collision energy (kip-ft.),

W = Vessel displacement tonnage (tonnes),

C_H = Hydrodynamic mass coefficient,

V = Design impact velocity (ft./sec.).

Equation 3.20 is based on the standard ½mV^2 formula for kinetic energy along with consideration of the hydrodynamic mass coefficient and necessary unit conversion factors. A separate calculation is required for the vessel in loaded and unloaded condition. Vessel displacement tonnage will usually differ based on the loading state of the vessel.

Using the kinetic energy of the vessel, the impact force transferred from the vessel to the pier can be calculated. A different set of equations is used to determine the impact force from ships and barge groups as the geometry and other properties of these vessels are significantly different.

3.1.4.2.1 Vessel Impact Force for Ships

The impact force of a ship colliding with a pier is based on the ship impact velocity and the deadweight tonnage of the ship. According to the AASHTO LRFD code Section 3.14.8 the force is computed as follows:

$$P_S = 8.15V\sqrt{DWT} \tag{3.21}$$

where:

P_S = Equivalent static vessel impact force (kips),

DWT = Deadweight tonnage of vessel (tonnes),

V = Design impact velocity (ft./sec.).

While it is not required for the LRFD calculations for annual frequency of bridge collapse, the ship bow damage length can be calculated as well. The bow damage depth is the horizontal length of the ship's bow that is crushed by the impact with the pier. It is computed based on the impact force averaged against the work path. The AASHTO LRFD code Section 3.14.9 quantifies ship bow damage depth as follows:

$$a_S = 1.54\left(\frac{KE}{P_S}\right) \tag{3.22}$$

where:

a_S = Bow damage length of the ship (ft.),

KE = Vessel collision energy (kip-ft.),

P_S = Ship impact force (kip) as determined in Equation 3.21.

The multiplier 1.54 in Equation 3.22 results from the product of three other coefficients: a factor of 1.25 accounts for the increase in average impact force over time; a factor of 1.11 accounts for the increase in average impact force to the 70 percent design fractile; and another factor of 1.11 provides an increase in the damage length to provide a similar level of design safety as that used to compute the ship collision force.

3.1.4.2.2 Vessel Impact Force for Barges

While the bow damage depth is not required for calculating impact forces of ships, for a barge it is a key component of the calculation. Barge impact force is directly obtained from the barge bow damage depth. The AASHTO LRFD code Section 3.14.12 expresses barge bow damage depth as follows:

$$a_B = 10.2\left(\sqrt{1 + \frac{KE}{5{,}672}} - 1\right) \tag{3.23}$$

where:

a_B = Barge bow damage length (ft.),

KE = Vessel collision energy (kip-ft.).

Based on the barge bow damage length the force imparted by the barge group on a pier can be calculated. The expressions for barge collision force on a pier are outlined in the AASHTO LRFD code Section 3.14.11 and are as follow:

If $a_B < 0.34$:

$$P_B = 4{,}112 a_B \tag{3.24}$$

If $a_B \geq 0.34$:

$$P_B = 1{,}349 + 110 a_B \tag{3.25}$$

where:

P_B = Equivalent static barge impact force (kip),

a_B = Barge bow damage length (ft.).

3.1.4.3 Limitations

As with geometric probability, the probability of collapse methodology outlined above was based on data acquired from ship-to-ship collisions. Fujii and Shiobara (1978) reported on ship-to-ship collisions and Cowiconsult (1987) adapted their results to allow the estimation of the probability of collapse caused by any vessel including barge groups for which no data were used in the code development. The AASHTO LRFD code acknowledges in the commentary that the procedure is proposed only due to a lack of data available on vessel collision with bridges.

In addition to the lack of data on barge collisions, the AASHTO LRFD method for calculating probability of collapse does not take into consideration the effects of progressive collapse nor the importance of a given pier in the overall bridge collapse. The AASHTO LRFD code implies that if one pier is considered failed, then the entire bridge has failed. This is a very conservative approach. to. It is likely that, in some situations, a pier may be completely removed and the bridge could still remain operational and repaired before a collapse occurred. Also, losing one pier could cause progressive collapse mechanism. The redundancy is not accounted for in the code calculations. Consideration for the conditional probability of bridge collapse given that a single pie has failed or is removed would add accuracy to the calculation of annual frequency of collapse.

3.2 AASHTO LRFD CODE LIMITATIONS

While the AASHTO LRFD code guidelines provide a comprehensive analysis approach to determining a return period for bridge collapse due to vessel impact, there are several limitations in the code. The AASHTO LRFD code attempts to simplify the modeling considerably based on past vessel impact studies. In most cases, the simplification allows the engineer to perform easier calculations. However, in several areas, the code simplification leads to an overly conservative approach. Some sections of the AASHTO LRFD code are based on sparse data and limited studies – e.g. computing the probability of bridge collapse due to impact from barge groups is based on data on ship-to-ship collision studies.

3.2.1 Data Limitations

One of the most significant weaknesses of the AASHTO LRFD code guidelines for vessel collision is the heavy reliance on actual data. While the AASHTO LRFD code equations can sometimes offer a reasonable estimate, the ability to obtain an estimate of annual frequency of bridge collapse dud to vessel impact relies on the availability of a plethora of actual data about the bridge, the channel, and the vessel traffic. It can be either very difficult to accumulate the necessary data and some data will change frequently. For instance, the depth of the water in a channel constantly changes as the channel fills with deposits and is dredged on a regular basis. It is difficult to know what the depth of the channel is at any give time. Other factors likely to change include vessel traffic, types of vessels, and channel currents.

3.3 CONCLUSION

The AASHTO LRFD design code attempts to provide a framework for the probability-based analysis of vessel impact on bridges. This framework is employed in example studies that follow and in the development of a standalone analysis program that will be discussed.

CHAPTER 4
Modifications to the AASHTO LRFD Approach

4.1 AREAS OF MODIFICATION

While the AASHTO LRFD method for the design of bridges for vessel collision can often provide reasonable answers, some of its limitations can be addressed. One such area relates to improving the calculation of probability of collapse. Very little research has been performed in the past on barge-to-pier collisions; therefore, the code bases calculations for probability of collapse entirely on ship-to-ship collision studies. To address this limitation, some preliminary work based on analysis (not testing) is proposed in order to yield different probability of collapse curves that might be of interest especially for barge impact on bridges.

4.2 MODIFICATION PROCEDURE

To develop a probability of collapse curve to be used as an alternative to Figure 3-4, it is necessary to carry out a series of analyses that will assess the likelihood that the bridge will collapse under different barge collision scenarios. The test runs are selected based upon a random sampling of important input variables for the analyses which yield impact forces and ultimate bridge strengths.

4.2.1 Test Variables

The input variables that will be modified include material properties, angle of impact, height or elevation of impact, and vessel loading. Separate analyses that yield vessel impact forces and ultimate strength for each sampled set of impact variables need to be carried out.

4.2.1.1 Variability of Material Properties

The material properties of the concrete and the steel reinforcement used in most bridge piers can vary considerably. In order to account for this, a normal distribution for concrete compressive strength is used. According to ACI (ACI, 2002) Table 5.3.2.2, the mean concrete compressive strength must exceed the specified concrete strength by 1,200 psi. Therefore the mean for 4,000 psi concrete would be 5,200 psi. The coefficient of variation for concrete compressive strength is taken as 10%. Thus we have:

$$\sigma = 0.1\mu \tag{4.1}$$

Where σ and μ are the standard deviation and the mean, respectively of concrete compressive strength.

To insure that a range of concrete compressive strengths are sampled, random numbers are generated from ten bins evenly distributed based on the cumulative distribution function of a normal random variable. Compressive strength values are thus obtained randomly in this statistical sampling procedure. The modulus of elasticity can be determined based on a function relationship with the compressive strength of the concrete. Table 4-1 presents the set of concrete compressive strength and modulus of elasticity values obtained for the test analyses.

Table 4-1: Sampled Material Properties for Concrete.

Step	f'c (ksi)	E (ksi)
1	4.19	3689.6
2	4.65	3888.5
3	4.79	3943.8
4	4.94	4005.5
5	5.08	4063.0
6	5.28	4140.1
7	5.35	4167.6
8	5.59	4263.5
9	5.76	4324.4
10	5.91	4381.9

4.2.1.2 Variability of the Angle of Impact

As a given barge group approaches a bridge and becomes aberrant, the angle at which it strikes a given bent or pier can vary. While it is possible to strike the bent at any angle between zero and 90 degrees, realistic angles of impact are likely to be far more limited. In order to have a manageable number of analyses to perform, the angle of impact for this study is limited to a maximum of 15 degrees in each direction from a head-on collision. A zero degree angle is considered a head-on collision and the range of impact angles is 30 degrees split into five steps of 7.5 degrees each. Since in most situations, positive and negative angles will yield the same results only three values, 15, 7.5 and 0 degrees are needed here. See Table 4-2.

Table 4-2: Angles of Impact Considered in the Analyses.

Step	Angle (deg)
1	15.0
2	7.5
3	0.0
4	-7.5
5	-15.0

4.2.1.3 Variability of Height/ Elevation of Impact

Since the water level in the channel changes at all times, the height or elevation along a pile where a barge group or vessel may strike is variable. The probability of collapse is expected to vary depending on the height of impact as the ultimate strength of the pier is different depending on the location where the load is applied. The load will be applied at two different locations, the normal water line and the high water line (See Table 4-3). In many cases, these two locations will be fairly close and hence additional impact locations are not considered.

Table 4-3: Impact Heights used in the Analyses.

Step	Location
1	HWL
2	NWL

4.2.1.4 Variability of Vessel Loading

At the time of the impact, a vessel may be fully loaded, completely unloaded, or at any loading condition in between. Analyses will be carried out only for the two extreme cases – loaded fully and unloaded (See Table 4-4).

Table 4-4: Vessel Loadings used in the Analyses.

Step	Loading
1	Loaded
2	Unloaded

4.2.1.5 Variable Limitations

While material properties, angle of impact, impact height, and vessel loading are being varied in the analyses, these are not the only variables that could be changed. Superstructure stiffness, boundary conditions, vessel velocity, vessel type, pier geometry, and degradation of materials properties could also have been modified. However, a limit of the number of variables is considered in order to have a manageable number of analyses to perform. While some variables (such as superstructure stiffness, boundary conditions, degradation of material properties) are easier to change and reflect modeling uncertainty, consideration for other variables such as vessel type, speed, and pier geometry would require extremely large number of analyses. Again, in the interest of having a manageable number of analyses to perform that focus on some of the key sources of variability, only the previously described analysis sets are proposed.

4.2.2 A Proposal for Improved Probability of Collapse Calculations

Considering all combinations of input parameters that are variable (Table 4-1 to Table 4-4), a total of 200 different analyses need to be performed. In each analysis, the ultimate lateral strength (H) of a pier and the impact force (P) transmitted by the vessel (barge) to the pier are determined. If P is found to be greater than H, a failure is deemed to have occurred. The fraction of analyses out of the 200 proposed that lead to failure is an alternative estimate to the probability of collapse value suggested by the AASHTO LRFD code.

Such estimates for the probability of bridge collapse due to vessel impact clearly have limitations in that they are model-based and not data-based. Moreover, numerous analyses are necessary for a single scenario in order to estimate the probability of collapse. Nevertheless, in this study, a software program for estimation of the annual frequency of bridge collapse due to vessel impact is developed to offer the user the option of alternative probability of collapse (PC) estimates which can be obtained using the method outlined in this chapter.

CHAPTER 5
Example Calculations

5.1 CALCULATION METHOD

As shown in Equation 3.2, the total annual frequency of bridge collapse due to vessel impacts is equal to the sum of the annual frequencies of collapse for each vessel-pier combination. A detailed example calculation is presented in this chapter. The calculations are performed using the separate program that was developed and discussed in Chapter 7. To facilitate the understanding of all the calculations, the data for each vessel-pier combination are first presented. Bridge and traffic data are *simulated* here in order to illustrate the 2004 AASHTO LRFD method. All of the equations used for these calculations and some background for their development can be found in Chapter 3.

5.2 THE COLORADO RIVER - FM 521 BRIDGE

5.2.1 Description of Data

5.2.1.1 Bridge and Channel Diagrams

Figure 5-1 shows a stick drawing of the Colorado River – FM 521 Bridge. The navigable waterway boundary and centerline are shown as are the high water line and the normal water line. Figure 5-2 shows a satellite image of the bridge and the surrounding region of interest.

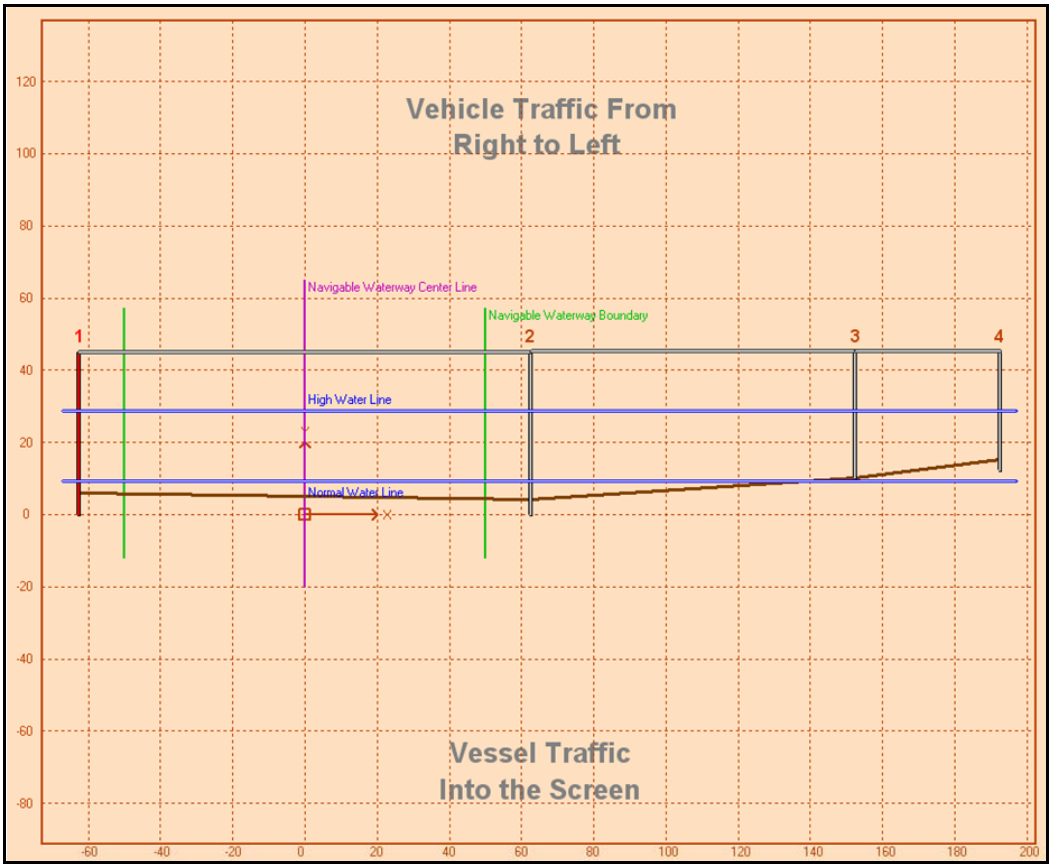


Figure 5-1: Colorado River – FM 521 Bridge Geometry.

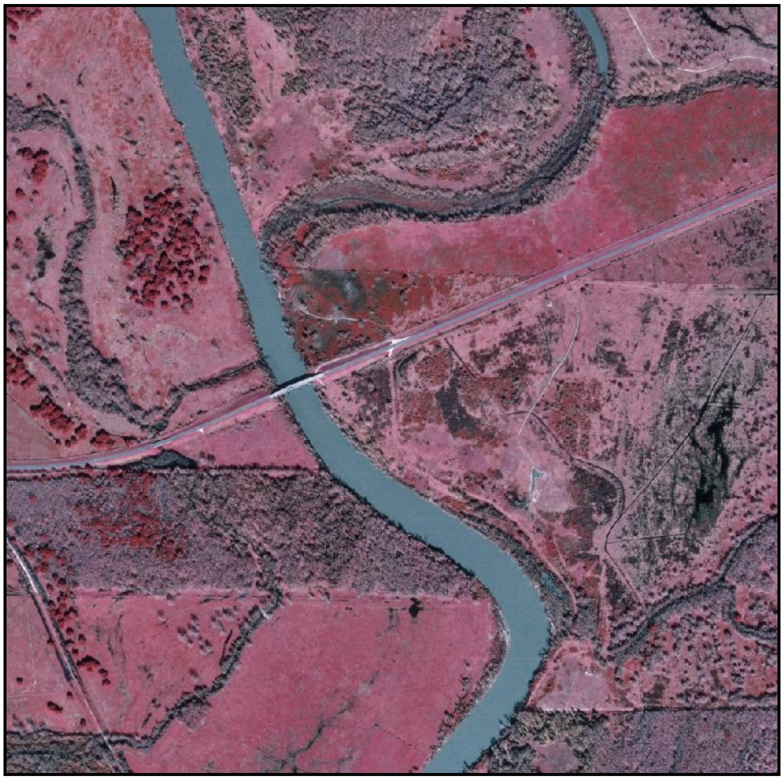


Figure 5-2: Satellite Image of the Colorado River – FM 521 Bridge and the Surrounding Region of Interest.

5.2.1.2 Bridge Data

The first step in performing the vessel collision analysis is to determine basic bridge properties and the importance classification of the bridge. Table 5-1 lists the name of the bridge, the TxDOT structure ID for the bridge, the waterway the bridge crosses, the mile marker on the waterway that the bridge is situated at, the roadway over the bridge, and the importance classification. Of all of these fields, only the importance classification will be needed later. The importance classification is determined in accordance with AASHTO LRFD code Section 3.14.3.

Table 5-1: Bridge Information

Bridge Name:	Colorado River - FM 521
TxDOT Structure ID:	131580084603009
Waterway:	Colorado River
Mile Marker:	100
Roadway:	FM 521
Importance Classification:	Regular

Once the basic information on the bridge is defined, additional information about the piers is collected. Each pier is first labeled for reference. In this case the bridge has four piers labeled from left to right (See Figure 5-1). For each pier, its distance from the navigable waterway centerline, the depth of the channel at the high water line (HWL) at that pier, the radius of the pier at where the high water line crosses, and the ultimate lateral strength (H) are recorded. All of this information is summarized in Table 5-2.

Table 5-2: Pier Data

Pier	Distance from CL	HWL Channel Depth	Diameter at HWL	H
	(ft)	(ft)	(ft)	(kips)
1	62.5	22.7	4	450
2	62.5	24.7	4	330
3	152.5	18.7	4	200
4	192.5	13.7	2	200

5.2.1.3 Channel Data

To perform the analysis, it is necessary to record the channel data. The parallel current velocity, perpendicular current velocity, minimum impact speed, navigable channel width, channel region type, channel turn angle, the traffic density need to be defined. It is important to be careful with units as the

AASHTO LRFD code equations contain empirical parameters that are often unit-specific. The channel data are summarized in Table 5-3.

Table 5-3: Channel Data

Parallel Current Velocity:	2	ft/s
Perpendicular Current Velocity:	1	ft/s
Minimum Impact Speed:	1.689	ft/s
Navigable Channel Width:	100	ft
Channel Region Type:	Transition	
Channel Turn Angle:	34	deg
Traffic Density:	Low	

5.2.1.4 Vessel Traffic Data

In addition to bridge, pier, and channel data, traffic data are also required in the analysis. Table 5-4 summarizes the information on all the vessels that will pass under the bridge. The class of vessel, the size of vessel, and the specific type of vessel are all defined. Details related to vessel class, size, and type are discussed in Chapter 7. It is important to note how many times each year a given vessel passes under the bridge, whether the vessel is loaded or unloaded, and the velocity of the vessel.

Table 5-4: Vessel Fleet Description

Vessel Name	Vessel Class	Vessel Size	Vessel Type	# Trips (Trips/Yr)	Loaded of Unloaded	Velocity (knots)
V1	Barge Group	TXDOT BG 1	N/A	101	Loaded	6
V2	Barge Group	TXDOT BG 2	N/A	29	Loaded	6
V3	Barge Group	TXDOT BG 3	N/A	15	Loaded	6

The specific geometry related to each vessel that passes under the bridge is detailed in Table 5-5, Table 5-6, and Table 5-7. The specific configuration of each of the barge groups is displayed in Figure 5-3, Figure 5-4, and Figure 5-5.

Table 5-5: Barge Group Description

Name	Barge Group Type	LOA	Width	Draft	Displacement
		(ft)	(ft)	(ft)	(tonne)
V1	TXDOT BG 1	452.0	35.0	9.0	3628.1
V2	TXDOT BG 2	655.0	35.0	9.0	5442.2
V3	TXDOT BG 3	850.0	35.0	9.0	7165.5

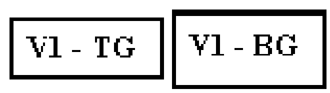


Figure 5-3: Vessel 1 – TXDOT BG 1 – Formation

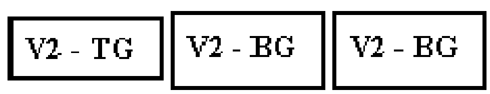


Figure 5-4: Vessel 2 – TXDOT BG 2 – Formation

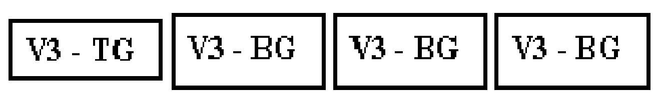


Figure 5-5: Vessel 3 – TXDOT BG 3 – Formation

Table 5-6: Tug Information

Name	Type	Horsepower	Length	Width	Draft	Displacement
			(ft)	(ft)	(ft)	(ton)
V1 - TG	TXDOT Tug	1	62.0	20.0	9.0	181.4
V2 - TG	TXDOT Tug	2	70.0	27.0	9.0	272.1
V3 - TG	TXDOT Tug	2	70.0	27.0	9.0	272.1

Table 5-7: Barge Information

Name	Type	Size	Length (ft)	Width (ft)	Draft (ft)	Displacement (tonne)
V1 - BG	Covered Hopper	Jumbo	195.0	35.0	8.7	1723.4
V2 - BG	Covered Hopper	Jumbo	195.0	35.0	8.7	1723.4
V3 - BG	Covered Hopper	Jumbo	195.0	35.0	8.7	1723.4

5.2.2 Calculation of Annual Frequency of Collapse

Using the data assembled in Section 5.2.1, computations leading to estimates of the annual frequency of collapse can now be carried out. The formulations for all the required calculations are detailed in Chapter 3.

5.2.2.1 Probability of Aberrancy (PA)

The expression for calculating probability of aberrancy is given in Equation 3.4. Each of the components that are involved in computing the probability of aberrancy is shown in Table 5-8. Probability of aberrancy is calculated for every vessel-pier combination.

Table 5-8: Probability of Aberrancy Calculations

Vessel	Pier	BR	R_B	R_C	R_{XC}	R_D	PA (1/Yrs)
1	1	0.00012	1.378	1.118	1.592	1.0	**0.000294**
1	2	0.00012	1.378	1.118	1.592	1.0	**0.000294**
1	3	0.00012	1.378	1.118	1.592	1.0	**0.000294**
1	4	0.00012	1.378	1.118	1.592	1.0	**0.000294**
2	1	0.00012	1.378	1.118	1.592	1.0	**0.000294**
2	2	0.00012	1.378	1.118	1.592	1.0	**0.000294**
2	3	0.00012	1.378	1.118	1.592	1.0	**0.000294**
2	4	0.00012	1.378	1.118	1.592	1.0	**0.000294**
3	1	0.00012	1.378	1.118	1.592	1.0	**0.000294**
3	2	0.00012	1.378	1.118	1.592	1.0	**0.000294**
3	3	0.00012	1.378	1.118	1.592	1.0	**0.000294**
3	4	0.00012	1.378	1.118	1.592	1.0	**0.000294**

The base rate is assigned depending on the type of vessel that is passing the pier. If the vessel is a ship or tug, the base rate is equal to .00006, for a barge or barge group this base rate is .00012. Table 5-9 shows the base rate for each vessel-pier combination.

Table 5-9: Base Rate (BR) Selection

Vessel	Pier	Vessel	BR
1	1	Barge	**0.00012**
1	2	Barge	**0.00012**
1	3	Barge	**0.00012**
1	4	Barge	**0.00012**
2	1	Barge	**0.00012**
2	2	Barge	**0.00012**
2	3	Barge	**0.00012**
2	4	Barge	**0.00012**
3	1	Barge	**0.00012**
3	2	Barge	**0.00012**
3	3	Barge	**0.00012**
3	4	Barge	**0.00012**

The correction factor for bridge location uses Equations 3.5, 3.6, and 3.7 depending on the region type. Chapter 3 also explains how one can determine what region type the bridge is located in. Table 5-10 displays the correction factor for bridge location for each of the vessel-pier combinations. The angle θ in Table 5-10 is computed for the study region using the satellite image in Figure 5-2.

Table 5-10: Correction Factor for Bridge Location (R_B) Calculations

Vessel	Pier	Region	θ	R_B
			(deg)	
1	1	Transition	34	**1.378**
1	2	Transition	34	**1.378**
1	3	Transition	34	**1.378**
1	4	Transition	34	**1.378**
2	1	Transition	34	**1.378**
2	2	Transition	34	**1.378**
2	3	Transition	34	**1.378**
2	4	Transition	34	**1.378**
3	1	Transition	34	**1.378**
3	2	Transition	34	**1.378**
3	3	Transition	34	**1.378**
3	4	Transition	34	**1.378**

The correction factors for parallel current and perpendicular current are given in Equations 3.8 and 3.9, respectively. It is important to note that these formulas involve unit-dependent empirical constants. The current velocity values and resulting correction factors used to determine probability of aberrancy are summarized in Table 5-11 and Table 5-12 for each vessel-pier combination.

Table 5-11: Correction Factor for Parallel Current (R_C) Calculations

Vessel	Pier	V_C	V_C	R_C
		(ft/sec)	(knots)	
1	1	2.0	1.185	**1.118**
1	2	2.0	1.185	**1.118**
1	3	2.0	1.185	**1.118**
1	4	2.0	1.185	**1.118**
2	1	2.0	1.185	**1.118**
2	2	2.0	1.185	**1.118**
2	3	2.0	1.185	**1.118**
2	4	2.0	1.185	**1.118**
3	1	2.0	1.185	**1.118**
3	2	2.0	1.185	**1.118**
3	3	2.0	1.185	**1.118**
3	4	2.0	1.185	**1.118**

Table 5-12: Correction Factor for Perpendicular Current (R_{XC}) Calculations

Vessel	Pier	V_{XC} (ft/sec)	V_{XC} (knots)	R_{XC}
1	1	1.0	0.592	**1.592**
1	2	1.0	0.592	**1.592**
1	3	1.0	0.592	**1.592**
1	4	1.0	0.592	**1.592**
2	1	1.0	0.592	**1.592**
2	2	1.0	0.592	**1.592**
2	3	1.0	0.592	**1.592**
2	4	1.0	0.592	**1.592**
3	1	1.0	0.592	**1.592**
3	2	1.0	0.592	**1.592**
3	3	1.0	0.592	**1.592**
3	4	1.0	0.592	**1.592**

The final correction factor for determining the probability of aberrancy is due to vessel traffic density. Chapter 3 explains how traffic density is represented and the resulting correction factors due to vessel traffic density are summarized in Table 5-13.

Table 5-13: Correction Factor for Traffic Density (R_D) Calculations

Vessel	Pier	Traffic Density	R_D
1	1	Low	**1.0**
1	2	Low	**1.0**
1	3	Low	**1.0**
1	4	Low	**1.0**
2	1	Low	**1.0**
2	2	Low	**1.0**
2	3	Low	**1.0**
2	4	Low	**1.0**
3	1	Low	**1.0**
3	2	Low	**1.0**
3	3	Low	**1.0**
3	4	Low	**1.0**

5.2.2.2 Geometric Probability (PG)

To determine geometric probability, the approach presented in Chapter 3 Section 3.1.3 is employed. The various parameters involved in the geometric probability calculations for each vessel pier combination are summaraized in Table 5-14.

Table 5-14: Geometric Probability (PG) Calculations

Vessel	Pier	X_P	B_P	B_V	LOA	X_1	X_2	PG
		(ft)	(ft)	(ft)	(ft)			(1/Yrs)
1	1	62.5	4.0	35.0	452.0	0.095	0.181	**0.034084**
1	2	62.5	4.0	35.0	452.0	0.095	0.181	**0.034084**
1	3	152.5	4.0	35.0	452.0	0.294	0.381	**0.032509**
1	4	192.5	2.0	35.0	452.0	0.385	0.467	**0.029819**
2	1	62.5	4.0	35.0	655.0	0.066	0.125	**0.023642**
2	2	62.5	4.0	35.0	655.0	0.066	0.125	**0.023642**
2	3	152.5	4.0	35.0	655.0	0.203	0.263	**0.023115**
2	4	192.5	2.0	35.0	655.0	0.266	0.322	**0.021581**
3	1	62.5	4.0	35.0	850.0	0.051	0.096	**0.018253**
3	2	62.5	4.0	35.0	850.0	0.051	0.096	**0.018253**
3	3	152.5	4.0	35.0	850.0	0.156	0.202	**0.018011**
3	4	192.5	2.0	35.0	850.0	0.205	0.248	**0.016925**

5.2.2.3 Probability of Collapse (PC)

Probability of collapse is determined by the method described in Section 3.1.4. While the ultimate lateral strength (H) is determined outside of the AASHTO LRFD calculations, the load due to the vessel impact may be estimated using the AASHTO LRFD code procedure. Table 5-15 shows the values of H and P used to estimate the probability of collapse for each of the vessel-pier combinations.

Table 5-15: Probability of Collapse (PC) Calculations

Vessel	Pier	H	P	H/P	PC
		(kip)	(kip)		(1/Yrs)
1	1	450	2274.7	0.198	**0.089041**
1	2	330	2274.7	0.145	**0.094896**
1	3	200	2192.6	0.091	**0.179043**
1	4	200	2155.7	0.093	**0.165002**
2	1	450	2610.0	0.172	**0.091862**
2	2	330	2610.0	0.126	**0.096966**
2	3	200	2537.4	0.079	**0.290605**
2	4	200	2504.5	0.080	**0.281296**
3	1	450	2889.9	0.156	**0.093716**
3	2	330	2889.9	0.114	**0.098325**
3	3	200	2824.1	0.071	**0.362635**
3	4	200	2794.3	0.072	**0.355830**

To determine the force, P, Equation 3.25 is used. The kinetic energy, KE, and barge bow damage length, a_B, needed to compute P for each vessel-pier calculation are given in Table 5-16. In this example, all of the vessels in this calculation are barge groups; hence, the same procedure for computing P is used for all vessel=pier combinations. Chapter 3 describes how the calculation would differ if ships were involved.

Table 5-16: Vessel Impact Force (P) Calculations

Vessel	Pier	KE	a_B	P
		(kip ft)	(ft)	(kip)
1	1	13219.4	8.415	**2274.7**
1	2	13219.4	8.415	**2274.7**
1	3	11735.0	7.669	**2192.6**
1	4	11088.1	7.334	**2155.7**
2	1	19914.2	11.464	**2610.0**
2	2	19914.2	11.464	**2610.0**
2	3	18378.0	10.803	**2537.4**
2	4	17698.6	10.505	**2504.5**
3	1	26276.7	14.008	**2889.9**
3	2	26276.7	14.008	**2889.9**
3	3	24718.4	13.410	**2824.1**
3	4	24024.3	13.139	**2794.3**

Table 5-17 shows how the kinetic energy (KE) is computed for each vessel-pier combinations based on Equation 3.20. The hydrodynamic mass coefficient is determined using the method described in the AASHTO LRFD code Section 3.14.7.

Table 5-17: Kinetic Energy (KE) Calculations

Vessel	Pier	HWL Depth	Draft	Underkeel Clearence	CH	W	V	KE
		(ft)	(ft)	(ft)		(tonne)	(ft/s)	(kip ft)
1	1	22.7	9.0	13.7	1.05	3628.1	10.066	**13219.4**
1	2	24.7	9.0	15.7	1.05	3628.1	10.066	**13219.4**
1	3	18.7	9.0	9.7	1.05	3628.1	9.484	**11735.0**
1	4	13.7	9.0	4.7	1.05	3628.1	9.219	**11088.1**
2	1	22.7	9.0	13.7	1.05	5442.2	10.088	**19914.2**
2	2	24.7	9.0	15.7	1.05	5442.2	10.088	**19914.2**
2	3	18.7	9.0	9.7	1.05	5442.2	9.691	**18378.0**
2	4	13.7	9.0	4.7	1.05	5442.2	9.510	**17698.6**
3	1	22.7	9.0	13.7	1.05	7165.5	10.099	**26276.7**
3	2	24.7	9.0	15.7	1.05	7165.5	10.099	**26276.7**
3	3	18.7	9.0	9.7	1.05	7165.5	9.795	**24718.4**
3	4	13.7	9.0	4.7	1.05	7165.5	9.656	**24024.3**

The method for determining vessel velocity (V) needed in computing kinetic energy is described in Section 3.1.4.2. The various parameters needed for the calculations are summarized in Table 5-18.

Table 5-18: Velocity (V) Calculations

Vessel	Pier	VT	V_{Min}	XC	LOA	XL	CLX	Pier Width	FaceX	V
		(ft/s)	(ft/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft/s)
1	1	10.134	1.689	50.0	452.0	1356.0	62.5	4.0	60.5	**10.066**
1	2	10.134	1.689	50.0	452.0	1356.0	62.5	4.0	60.5	**10.066**
1	3	10.134	1.689	50.0	452.0	1356.0	152.5	4.0	150.5	**9.484**
1	4	10.134	1.689	50.0	452.0	1356.0	192.5	2.0	191.5	**9.219**
2	1	10.134	1.689	50.0	655.0	1965.0	62.5	4.0	60.5	**10.088**
2	2	10.134	1.689	50.0	655.0	1965.0	62.5	4.0	60.5	**10.088**
2	3	10.134	1.689	50.0	655.0	1965.0	152.5	4.0	150.5	**9.691**
2	4	10.134	1.689	50.0	655.0	1965.0	192.5	2.0	191.5	**9.510**
3	1	10.134	1.689	50.0	850.0	2550.0	62.5	4.0	60.5	**10.099**
3	2	10.134	1.689	50.0	850.0	2550.0	62.5	4.0	60.5	**10.099**
3	3	10.134	1.689	50.0	850.0	2550.0	152.5	4.0	150.5	**9.795**
3	4	10.134	1.689	50.0	850.0	2550.0	192.5	2.0	191.5	**9.656**

5.2.2.4 Vessel Frequency (N)

For each vessel-pier combination, the number of trips per year by each vessel is multiplied by a growth factor to account for increased future vessel traffic. This calculation is summarized in Table 5-19.

Table 5-19: Projected Vessel Frequency (N) Calculations

Vessel	Pier	Growth Factor	# Trips (Trips/Yr)	N (Trips/Yr)
1	1	1.2	101	**121.2**
1	2	1.2	101	**121.2**
1	3	1.2	101	**121.2**
1	4	1.2	101	**121.2**
2	1	1.2	29	**34.8**
2	2	1.2	29	**34.8**
2	3	1.2	29	**34.8**
2	4	1.2	29	**34.8**
3	1	1.2	15	**18.0**
3	2	1.2	15	**18.0**
3	3	1.2	15	**18.0**
3	4	1.2	15	**18.0**

5.2.2.5 Return Period

Finally, using Equation 3.1, the annual frequency of bridge collapse is computed for each vessel-pier combination. Then, all of these annual frequencies of collapse are summed, and the reciprocal of this frequency yields the return period associated with bridge collapse due to vessel impact. This calculation is summarized in Table 5-20.

Table 5-20: Return Period Calculations

Vessel	Pier	N	PA	PG	PC	AFC	
		(Trips/Yr)	(1/Yrs)	(1/Yrs)	(1/Yrs)	(1/Yrs)	
1	1	121.2	0.000294	0.034084	0.089041	0.000108	
1	2	121.2	0.000294	0.034084	0.094896	0.000115	
1	3	121.2	0.000294	0.032509	0.179043	0.000208	
1	4	121.2	0.000294	0.029819	0.165002	0.000176	
2	1	34.8	0.000294	0.023642	0.091862	0.000022	
2	2	34.8	0.000294	0.023642	0.096966	0.000023	
2	3	34.8	0.000294	0.023115	0.290605	0.000069	
2	4	34.8	0.000294	0.021581	0.281296	0.000062	
3	1	18.0	0.000294	0.018253	0.093716	0.000009	
3	2	18.0	0.000294	0.018253	0.098325	0.000010	
3	3	18.0	0.000294	0.018011	0.362635	0.000035	
3	4	18.0	0.000294	0.016925	0.355830	0.000032	
				Sum AFC:		**0.000869**	**1 /Yrs**
				Return Period:		**1150.7**	**Years**

$$1150.7 > 1000 \tag{5.1}$$

This bridge passes the AASHTO LRFD specifications.

Since this bridge is classified as “Regular” in terms of importance, its return period must be larger than 1000 years. Since this bridge has a return period of 1150.7 years, it passes the AASHTO LRFD requirements.

5.3 THE SAN JACINTO RIVER – EASTBOUND IH-10 BRIDGE

This second bridge example is provided to reiterate the methods used in Section 5.2. Only the tables and figures are provided as the equations and methods are identical to those used in the previous example.

5.3.1 Description of Data

5.3.1.1 Bridge and Channel Diagrams

The bridge and channel diagrams are summarized in Figure 5-6 and Figure 5-7.

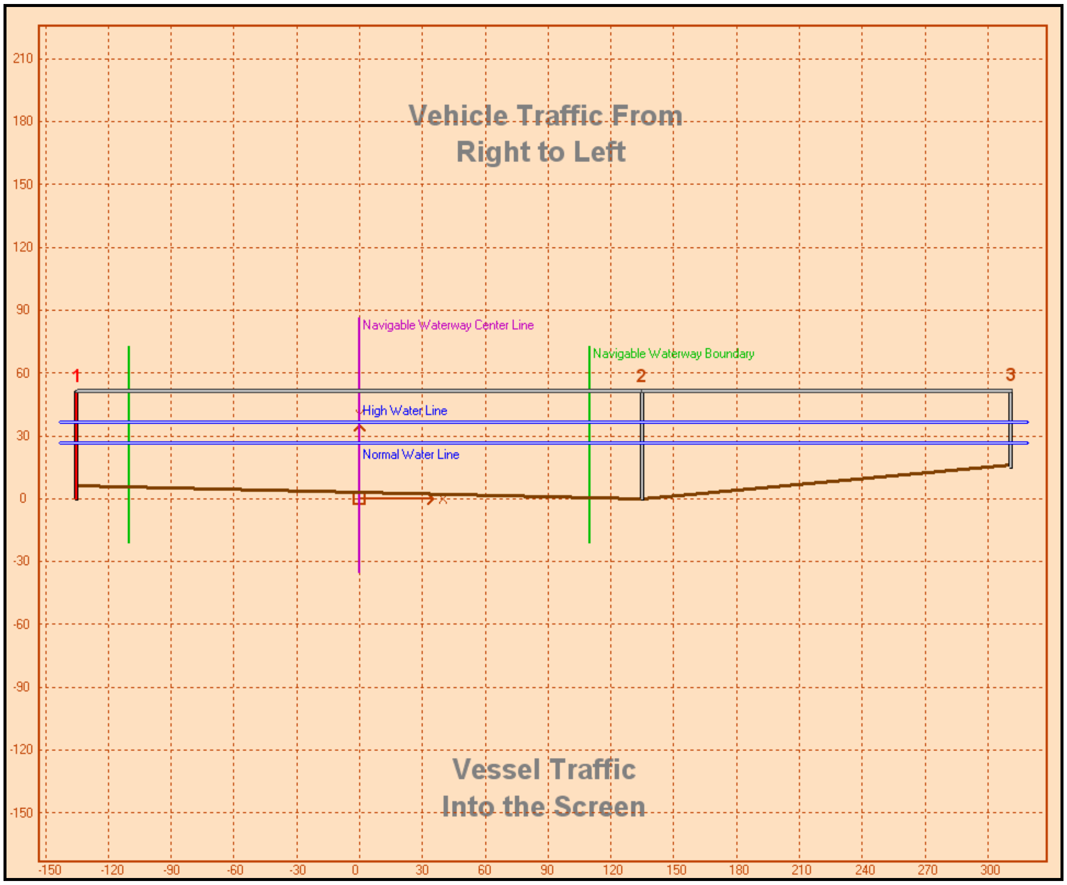


Figure 5-6: San Jacinto River – IH 10 Bridge Geometry

Figure 5-7: Satellite View of the San Jacinto River – IH 10 Bridge

5.3.1.2 Bridge Data

Table 5-21: Bridge Information

Bridge Name:	San Jacinto River - Eastbound IH-10
TxDOT Structure ID:	121020050801317
Waterway:	San Jacinto River
Mile Marker:	1
Roadway:	Eastbound IH-10
Importance Classification:	Regular

Table 5-22: Pier Data

Pier	Distance from CL	HWL Channel Depth	Diameter at HWL	H
	(ft)	(ft)	(ft)	(kips)
1	135.0	30.7	4.75	997
2	135.0	36.7	4.75	997
3	311.0	20.7	3.75	815

5.3.1.3 Channel Data

Table 5-23: Channel Data

Parallel Current Velocity:	2.0	ft/s
Perpendicular Current Velocity:	1.0	ft/s
Minimum Impact Speed:	1.689	ft/s
Navigable Channel Width:	220	ft
Channel Region Type:	Bend	
Channel Turn Angle:	15	deg
Traffic Density:	Low	

5.3.1.4 Vessel Traffic Data

Table 5-24: Vessel Fleet Description

Vessel Name	Vessel Class	Vessel Size	Vessel Type	# Trips	Loaded of Unloaded	Velocity
				(Trips/Yr)		(knots)
V1	Barge Group	TXDOT BG 4	N/A	677	Loaded	6
V2	Barge Group	TXDOT BG 4	N/A	677	Unloaded	6

Table 5-25: Barge Group Description

Name	Barge Group Type	LOA	Width	Draft	Displacement
		(ft)	(ft)	(ft)	(tonne)
V1	TXDOT BG 4	257.0	35.0	9.0	1542.0
V2	TXDOT BG 4	257.0	35.0	9.0	568.0

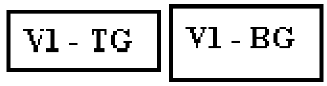


Figure 5-8: Vessel 1 – TXDOT BG 4 (V1 Loaded) – Formation

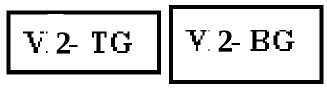


Figure 5-9: Vessel 1 – TXDOT BG 4 (V2 Empty)– Formation

Table 5-26: Tug Information

Name	Type	Horsepower	Length	Width	Draft	Displacement
			(ft)	(ft)	(ft)	(ton)
V1 - TG	TXDOT Tug	1	62.0	20.0	9.0	200.0
V2 - TG	TXDOT Tug	1	62.0	20.0	9.0	200.0

Table 5-27: Barge Information

Name	Type	Size	Length	Width	Draft	Displacement
			(ft)	(ft)	(ft)	(ton)
V1 - BG	Covered Hopper	Jumbo	195.0	35.0	7.0	1500.0
V2 - BG	Covered Hopper	Jumbo	195.0	35.0	2.0	425.8

5.3.2 Calculation of Annual Frequency of Collapse

5.3.2.1 Probability of Aberrancy (PA)

Table 5-28: Probability of Aberrancy Calculations

Vessel	Pier	BR	R_B	R_C	R_{XC}	R_D	PA (1/Yrs)
1	1	0.00012	1.333	1.118	1.592	1.0	**0.000285**
1	2	0.00012	1.333	1.118	1.592	1.0	**0.000285**
1	3	0.00012	1.333	1.118	1.592	1.0	**0.000285**
2	1	0.00012	1.333	1.118	1.592	1.0	**0.000285**
2	2	0.00012	1.333	1.118	1.592	1.0	**0.000285**
2	3	0.00012	1.333	1.118	1.592	1.0	**0.000285**

Table 5-29: Base Rate (BR) Selection

Vessel	Pier	Vessel	BR
1	1	Barge	**0.00012**
1	2	Barge	**0.00012**
1	3	Barge	**0.00012**
2	1	Barge	**0.00012**
2	2	Barge	**0.00012**
2	3	Barge	**0.00012**

Table 5-30: Correction Factor for Bridge Location (R_B) Calculations

Vessel	Pier	Region	θ (deg)	R_B
1	1	Bend	15	**1.333**
1	2	Bend	15	**1.333**
1	3	Bend	15	**1.333**
2	1	Bend	15	**1.333**
2	2	Bend	15	**1.333**
2	3	Bend	15	**1.333**

Table 5-31: Correction Factor for Parallel Current (R_C) Calculations

Vessel	Pier	V_C (ft/sec)	V_C (knots)	R_C
1	1	2.0	1.185	**1.118**
1	2	2.0	1.185	**1.118**
1	3	2.0	1.185	**1.118**
2	1	2.0	1.185	**1.118**
2	2	2.0	1.185	**1.118**
2	3	2.0	1.185	**1.118**

Table 5-32: Correction Factor for Perpendicular Current (R_{XC}) Calculations

Vessel	Pier	V_{XC} (ft/sec)	V_{XC} (knots)	R_{XC}
1	1	1.0	0.592	**1.592**
1	2	1.0	0.592	**1.592**
1	3	1.0	0.592	**1.592**
2	1	1.0	0.592	**1.592**
2	2	1.0	0.592	**1.592**
2	3	1.0	0.592	**1.592**

Table 5-33: Correction Factor for Traffic Density (R_D) Calculations

Vessel	Pier	Traffic Density	R_D
1	1	Low	**1.0**
1	2	Low	**1.0**
1	3	Low	**1.0**
2	1	Low	**1.0**
2	2	Low	**1.0**
2	3	Low	**1.0**

5.3.2.2 Geometric Probability (PG)

Table 5-34: Geometric Probability (PG) Calculations

Vessel	Pier	X_P	B_P	B_V	LOA	X_1	X_2	PG
		(ft)	(ft)	(ft)	(ft)			(1/Yrs)
1	1	135	4.75	35.0	257.0	0.448	0.603	**0.053713**
1	2	135	4.75	35.0	257.0	0.448	0.603	**0.053713**
1	3	311	3.75	35.0	257.0	1.135	1.286	**0.028937**
2	1	135	4.75	35.0	257.0	0.448	0.603	**0.053713**
2	2	135	4.75	35.0	257.0	0.448	0.603	**0.053713**
2	3	311	3.75	35.0	257.0	1.135	1.286	**0.028937**

5.3.2.3 Probability of Collapse (PC)

Table 5-35: Probability of Collapse (PC) Calculations

Vessel	Pier	H	P	H/P	PC
		(kip)	(kip)		(1/Yrs)
1	1	997	1792.8	0.556	**0.049271**
1	2	997	1792.8	0.556	**0.049271**
1	3	815	1629.8	0.500	**0.055493**
2	1	997	1530.2	0.652	**0.038677**
2	2	997	1530.2	0.652	**0.038677**
2	3	815	1459.9	0.558	**0.049033**

Table 5-36: Vessel Impact Force (P) Calculations

Vessel	Pier	KE	a_B	P
		(kip ft)	(ft)	(kip)
1	1	5374.2	4.034	**1792.8**
1	2	5374.2	4.034	**1792.8**
1	3	3194.3	2.553	**1629.8**
2	1	1979.6	1.647	**1530.2**
2	2	1979.6	1.647	**1530.2**
2	3	1176.6	1.008	**1459.9**

Table 5-37: Kinetic Energy (KE) Calculations

Vessel	Pier	HWL Depth	Draft	Underkeel Clearence	CH	W	V	KE
		(ft)	(ft)	(ft)		(tonne)	(ft/s)	(kip ft)
1	1	30.7	9.0	21.7	1.05	1542.0	9.845	**5374.2**
1	2	36.7	9.0	27.7	1.05	1542.0	9.845	**5374.2**
1	3	20.7	9.0	11.7	1.05	1542.0	7.590	**3194.3**
2	1	30.7	9.0	21.7	1.05	568.0	9.845	**1979.6**
2	2	36.7	9.0	27.7	1.05	568.0	9.845	**1979.6**
2	3	20.7	9.0	11.7	1.05	568.0	7.590	**1176.6**

Table 5-38: Velocity (V) Calculations

Vessel	Pier	VT	V_{Min}	XC	LOA	XL	CLX	Pier Width	FaceX	V
		(ft/s)	(ft/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft/s)
1	1	10.134	1.689	110.0	257.0	771.0	135.0	4.75	132.625	**9.845**
1	2	10.134	1.689	110.0	257.0	771.0	135.0	4.75	132.625	**9.845**
1	3	10.134	1.689	110.0	257.0	771.0	311.0	3.75	309.125	**7.590**
2	1	10.134	1.689	110.0	257.0	771.0	135.0	4.75	132.625	**9.845**
2	2	10.134	1.689	110.0	257.0	771.0	135.0	4.75	132.625	**9.845**
2	3	10.134	1.689	110.0	257.0	771.0	311.0	3.75	309.125	**7.590**

5.3.2.4 Vessel Frequency (N)

Table 5-39: Projected Vessel Frequency (N) Calculations

Vessel	Pier	Growth Factor	# Trips	N
			(Trips/Yr)	(Trips/Yr)
1	1	1.2	677	**812.4**
1	2	1.2	677	**812.4**
1	3	1.2	677	**812.4**
2	1	1.2	677	**812.4**
2	2	1.2	677	**812.4**
2	3	1.2	677	**812.4**

5.3.2.5 Return Period

Table 5-40: Return Period Calculations

Vessel	Pier	N	PA	PG	PC	AFC	
		(Trips/Yr)	(1/Yrs)	(1/Yrs)	(1/Yrs)	(1/Yrs)	
1	1	812.4	0.000285	0.053713	0.049271	0.000613	
1	2	812.4	0.000285	0.053713	0.049271	0.000613	
1	3	812.4	0.000285	0.028937	0.055493	0.000372	
2	1	812.4	0.000285	0.053713	0.038677	0.000481	
2	2	812.4	0.000285	0.053713	0.038677	0.000481	
2	3	812.4	0.000285	0.028937	0.049033	0.000329	
				Sum AFC:		**0.002888**	**1 /Yrs**
				Return Period:		**346.3**	**Years**

$$346.3 < 1000 \tag{5.2}$$

This bridge does not pass the AASHTO LRFD specifications.

This bridge has a return period for collapse due to vessel impact that is shorter than 1000 years and, hence, fails to meet the AASHTO LRFD specification for a “regular” bridge.

5.4 CONCLUSIONS

The preceding examples illustrate the procedure involved in Method II of the AASHTO LRFD code specifications. This method aims to provide estimates of the annual frequency of collapse of a bridge due to vessel impact. The computations summarized here can be included in a computer analysis program which was developed for this study and is discussed in Chapter 7.

CHAPTER 6

Typical Bridge Analysis Results and Insights

6.1 Bridge Performance and Recommendations

This chapter will focus on the results of a complete analysis of three distinct bridges. For each bridge, the return period is provided and a discussion detailing important parameters influencing the bridge vulnerability is included. Figure 6-1 lists the bridges that will be discussed in this chapter along with the results from the analysis using the AASHTO LRFD approach.

Bridge Name	Return Period (years)	Pass/Fail
Colorado River - FM 521	1152	Pass
San Jacinto River - EB IH 10	346	Fail
GIWW - PR 22	12019	Pass

Figure 6-1: Summary of Bridges Analyzed

6.1.1 Colorado River – FM 521

The Colorado River – FM 521 Bridge has a return period of 1152 year which passes the AASHTO LRFD requirements of a 1000-year return period for a bridge with an importance classification of "Regular." While this bridge has a return period which is acceptable, it is still useful to examine which piers and vessels most influence the annual frequency of bridge collapse. Figure 6-2 shows the bridge geometry and Figure 6-3 shows a satellite image of the bridge and the surrounding region of interest.

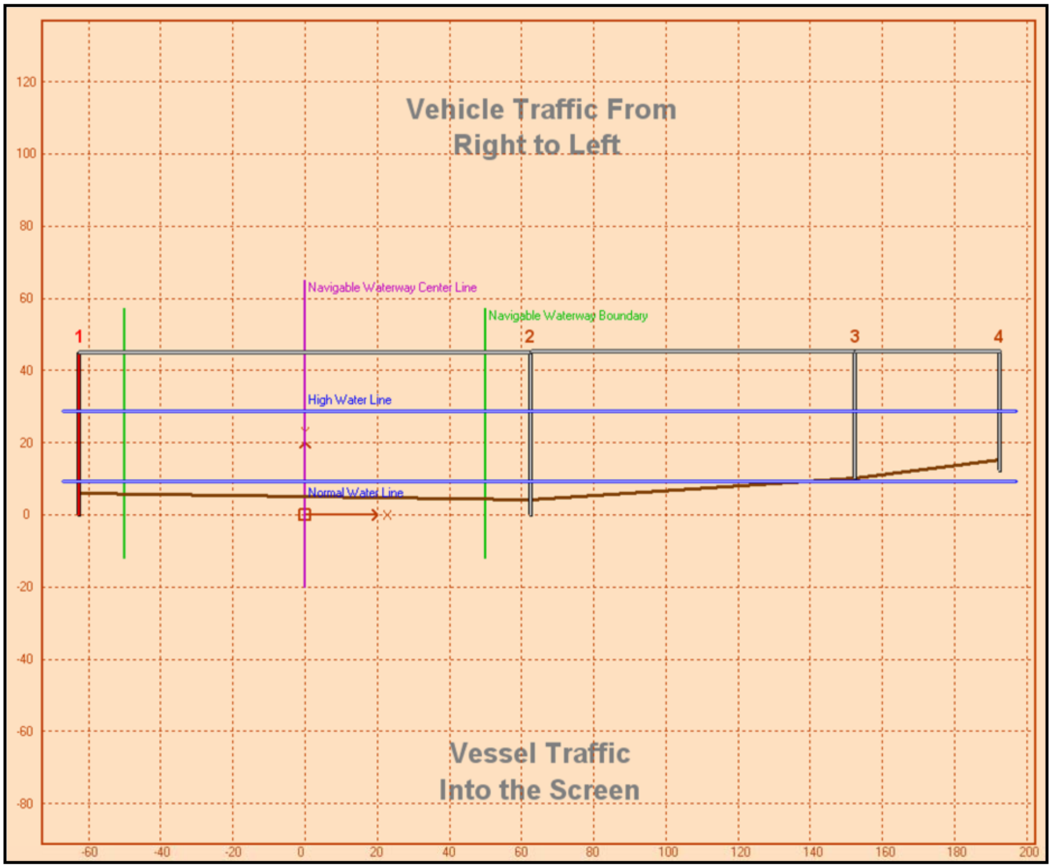


Figure 6-2: Colorado River – FM 521 Bridge Geometry.

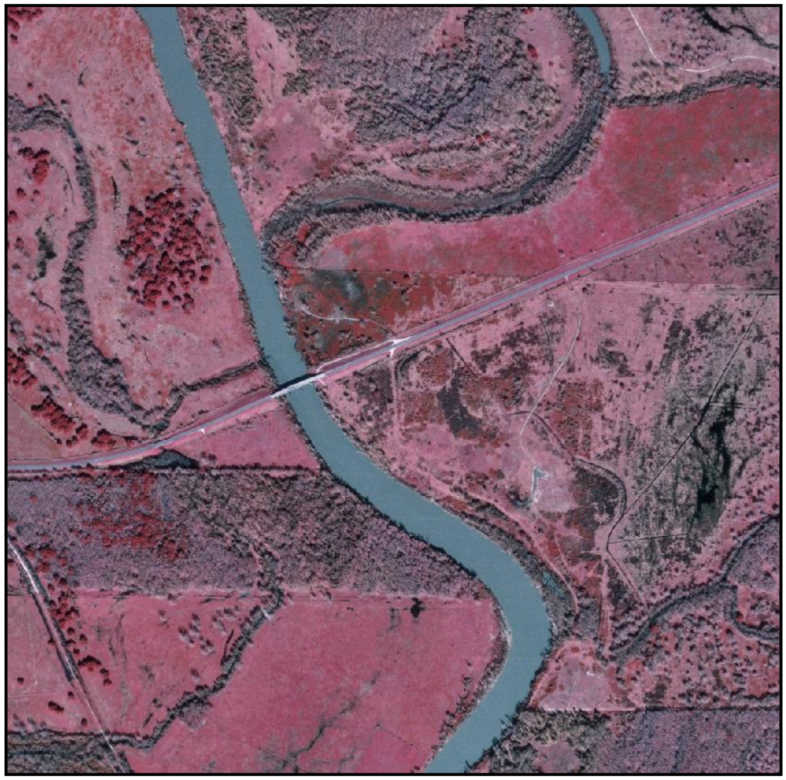


Figure 6-3: Satellite Image of the Colorado River – FM 521 Bridge and the Surrounding Region of Interest.

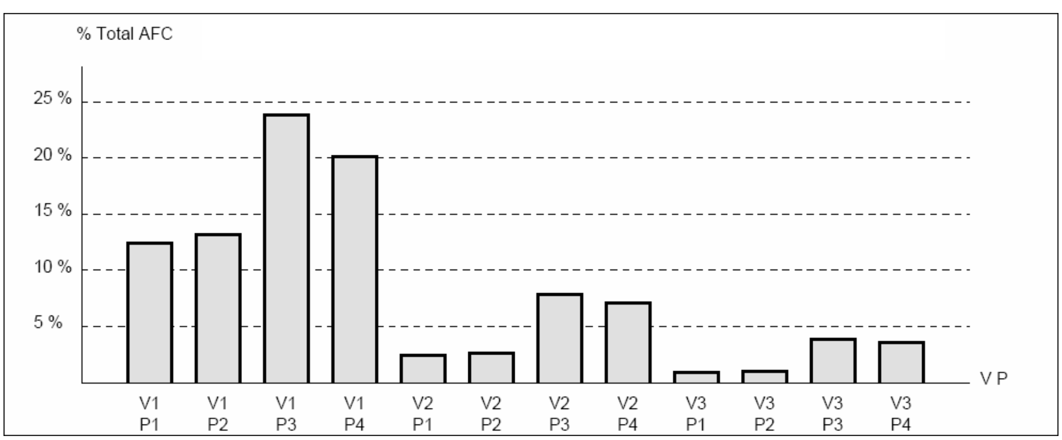


Figure 6-4: Contribution towards the annual frequencies of collapse of a particular vessel passing a particular of the Colorado River – FM 521Bridge (from the VIOB Report)

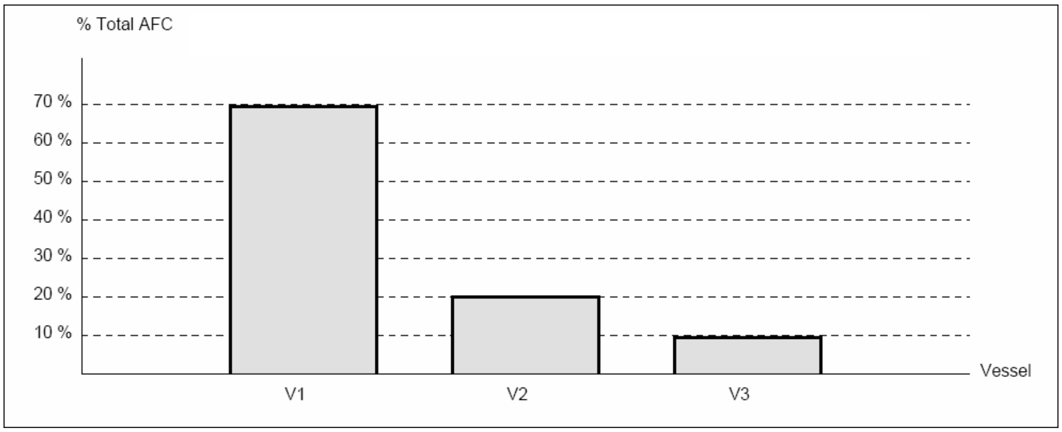


Figure 6-5: Contribution towards the annual frequencies of collapse of each vessel passing all piers of the Colorado River – FM 521Bridge (from the VIOB Report)

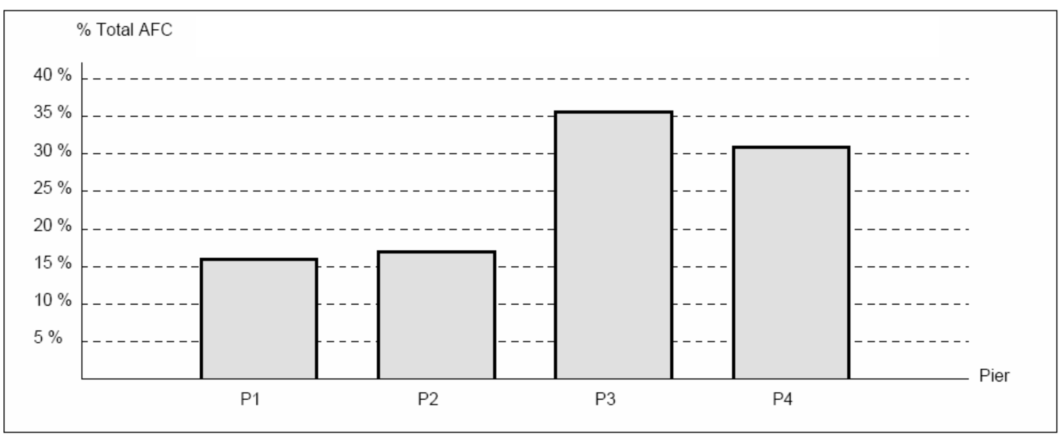


Figure 6-6: Contribution towards the annual frequencies of collapse of all vessels passing a particular pier of the Colorado River – FM 521 Bridge (from the VIOB Report)

Vessel Name	Vessel Class	Vessel Type	Vessel Size	Vessel Frequency	Loaded or Unloaded	Vessel Velocity
				(Trips/Year)		(knots)
V1	Barge Group	TXDOT BG 1	N/A	101	Loaded	6
V2	Barge Group	TXDOT BG 2	N/A	29	Loaded	6
V3	Barge Group	TXDOT BG 3	N/A	15	Loaded	6

Figure 6-7: Vessel fleet components for the Colorado River – FM 521 Bridge (from the VIOB Report)

Pier Number:		Pier 1	Pier 2	Pier 3	Pier 4
Pier Height:	ft	45	45	35	33
Pier Bottom Elevation:	ft	0	0.16	10.16	12.16
Channel Elevation:	ft	6.16	4.16	10.16	15.16
User X Location:	ft	-62.5	62.5	152.5	192.5
Ultimate Transverse Pier Strength:	kips	450	330	200	200
Pier X-Section Shape:		Circle	Circle	Circle	Circle
Pier X-Section Depth:	ft	4	4	4	2
Pier X-Section Width:	ft	4	4	4	2
Pier X-Section Angle:	deg	0	0	0	0

Figure 6-8: Pier Information for the Colorado River – FM 521 Bridge (from the VIOB Report)

From the results comparison section of the VIOB Report (discussed further in Chapter 7) for the Colorado River – FM 521 Bridge several trends may be noted. First, by studying Figure 6-4 and Figure 6-5, it can be seen that Vessel 1 has a much greater influence on the return period than does Vessels 2 and 3. However, Vessel 3 has a much larger displacement than Vessel 1 and both vessels move at the same velocity (See Chapter 5). It can be concluded that the dominant variable in the calculations is vessel trip frequency. Figure 6-7 lists the trip frequency of each type of vessel that passes this bridge. Each year, Vessel 1 travels past the bridge 101 times while Vessel 3 travels past it only 15 times.

Vessel 2 travels past the bridge 29 times per year. There is almost a direct relationship between the vessel frequency and the percentage contribution to the total annual frequency of collapse of the bridge.

Upon studying at Figure 6-6 in can be seen that Piers 3 and 4 have a much far greater influence on the return period than Piers 1 and 2. At first, this seems unexpected because Piers 1 and 2 are closer to the centerline of the navigable channel than Piers 3 and 4. Piers closer to the centerline generally have a higher geometric probability. However, upon further inspection, it is clear that the controlling factor in this calculation is the probability of collapse, and as seen in Figure 6-8, Piers 3 and 4 both have considerably lower ultimate lateral strengths (H) than do Piers 1 and 2. A low H value leads to a high probability of collapse and hence, Piers 3 and 4 have a strong influence on the final return period associated with collapse of the Colorado River – FM 521 Bridge. By studying Figure 6-4, both factors identified, namely the vulnerability of Piers 3 and 4 and the importance of Vessel 1 are seen to dominate the risk to this bridge.

6.1.2 San Jacinto River – EB IH 10

The San Jacinto River – EB IH 10 Bridge is not as straightforward as the Colorado River – FM 521 Bridge. The return period for this bridge is only 346 years, considerably lower than the AASHTO LRFD required 1000 years for a "regular" bridge. By interpreting the results, a feasible solution for increasing the return period may be determined. Figure 6-9 shows the bridge geometry and Figure 6-10 shows a satellite image of the bridge and the surrounding region of interest.

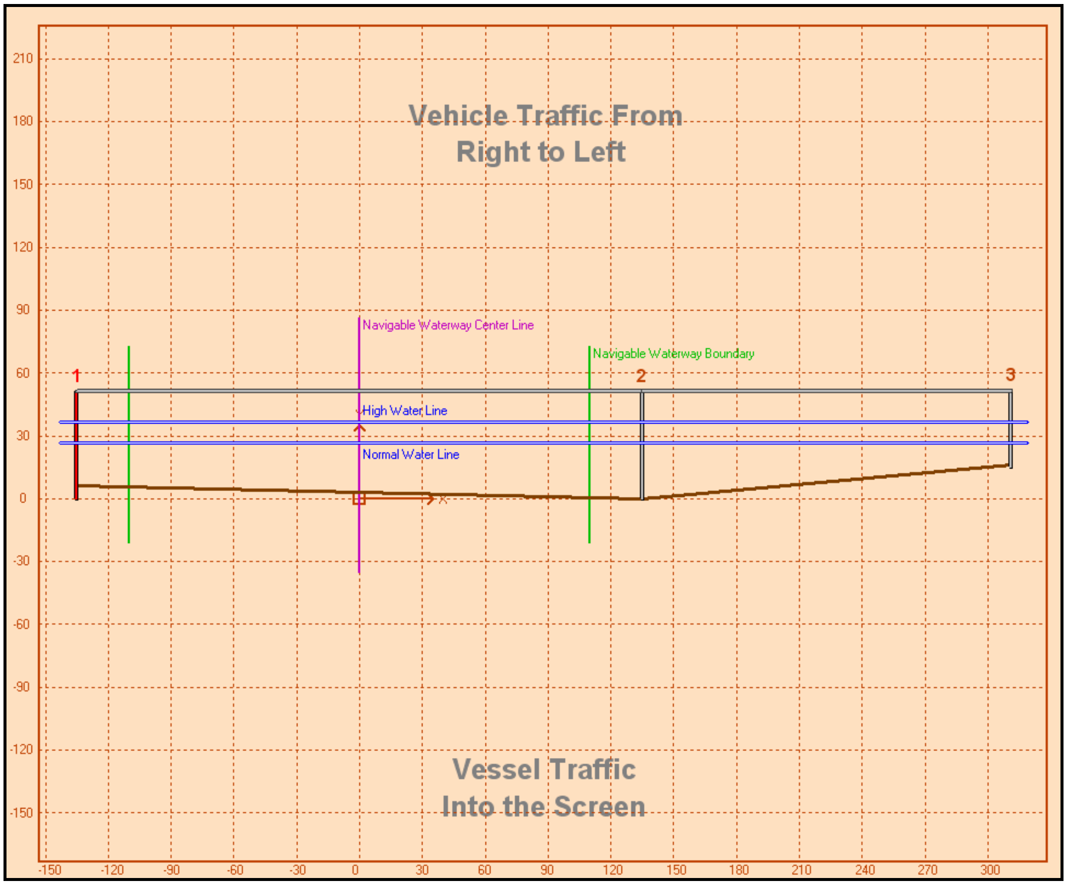


Figure 6-9: San Jacinto River – IH 10 Bridge Geometry

Figure 6-10: Satellite View of the San Jacinto River – IH 10 Bridge and the Surrounding Region of Interest.

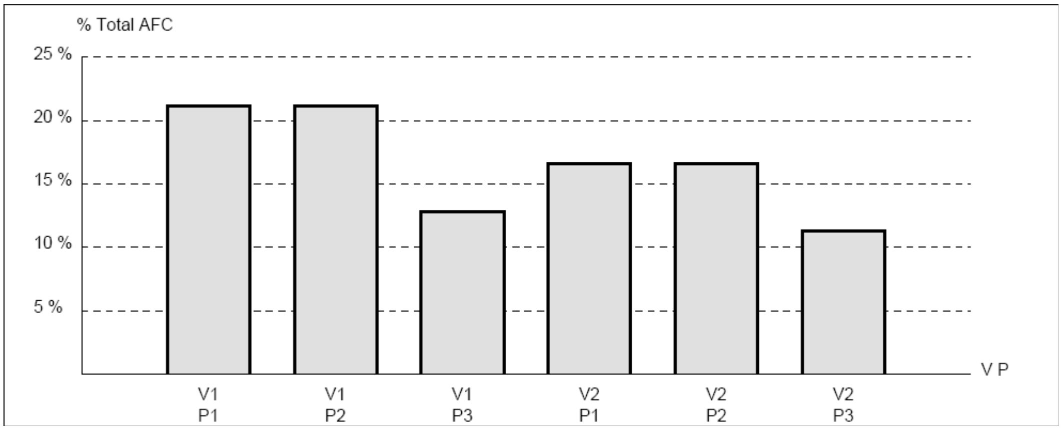


Figure 6-11: Contribution towards the annual frequencies of collapse of a particular vessel passing a particular pier of the San Jacinto River – EB IH 10 Bridge (from the VIOB Report)

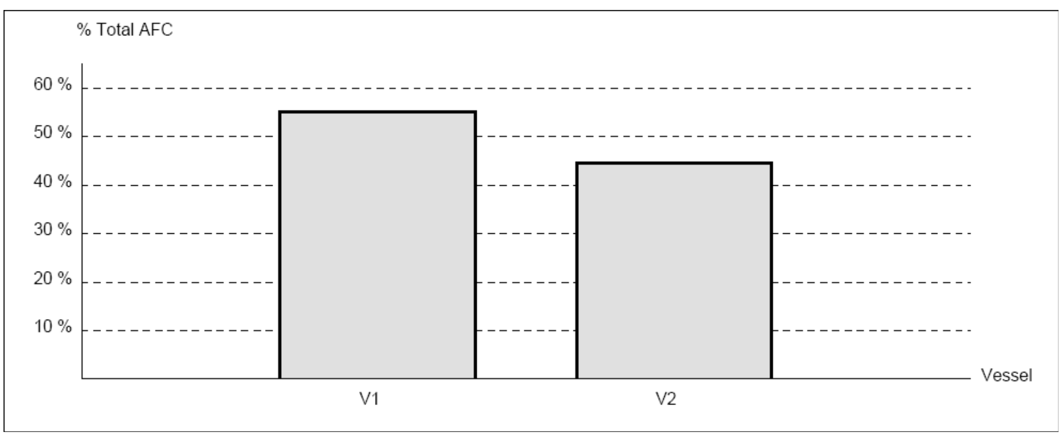


Figure 6-12: Contribution towards the annual frequencies of collapse of a particular vessel passing all piers of the San Jacinto River – EB IH 10 Bridge (from the VIOB Report)

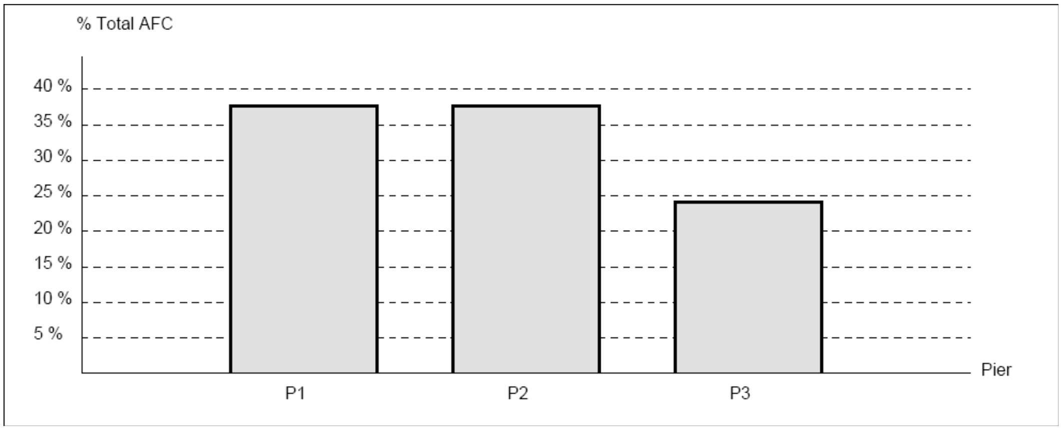


Figure 6-13: Contribution towards the annual frequencies of collapse of all vessels passing a particular pier of the San Jacinto River – EB IH 10 Bridge (from the VIOB Report)

Vessel i - Pier j	N	PA	PG	PC	AFC
Vessel 1 - Pier 1	812.4	0.000285	0.053714	0.049254	0.000613
Vessel 1 - Pier 2	812.4	0.000285	0.053714	0.049254	0.000613
Vessel 1 - Pier 3	812.4	0.000285	0.028937	0.055482	0.000372
Vessel 2 - Pier 1	812.4	0.000285	0.053714	0.038662	0.000481
Vessel 2 - Pier 2	812.4	0.000285	0.053714	0.038662	0.000481
Vessel 2 - Pier 3	812.4	0.000285	0.028937	0.049025	0.000329
				Total AFC:	**0.002889**

Figure 6-14: Annual frequency of collapse values for each vessel-pier combination for the San Jacinto River – EB IH 10 Bridge (from the VIOB Report)

Upon studying Figure 6-11, Figure 6-12, and Figure 6-13, no obvious trends can be seen. Figure 6-11 shows that there is a fairly equal contribution towards the bridge's risk from each of the vessel-pier combinations. However, it is necessary to increase the return period associated with collapse of this bridge since it is considerably lower than the acceptable value of 1000 years. The most obvious way to improve an existing bridge is to place a dolphin in front of the piers to mitigate vessel collision effects significantly. Placing a dolphin in front of a pier effectively changes that pier's probability of collapse to almost zero and therefore makes its annual frequency of collapse also zero. Installation of a dolphin is very expensive though and, therefore, minimizing the number of piers that need to be protected can save a considerable amount of money. Figure 6-13 clearly indicates that Piers 1 and 2 are of greater risk than Pier 3. Therefore, placing dolphins in front of those two piers could solve the problem of the low return period. In this case, the new return period increases to 1,426 years and therefore makes this bridge acceptable under the 2004 AASHTO LRFD standards. The completion of this analysis suggests that a dolphin is not needed to protect Pier 3.

6.1.3 GIWW – PR 22

The GIWW – PR 22 Bridge illustrates a few different issues that are not a concern for the first two bridges discussed. Having a return period of 12,019 years, the GIWW – PR 22 Bridge clearly passes the AASHTO LRFD requirement of 1000 years for a "regular" bridge. A detailed study of how this bridge achieves such a high return period is still useful. Figure 6-15 shows the bridge geometry and Figure 6-16 shows a satellite image of the bridge and the surrounding region of interest.

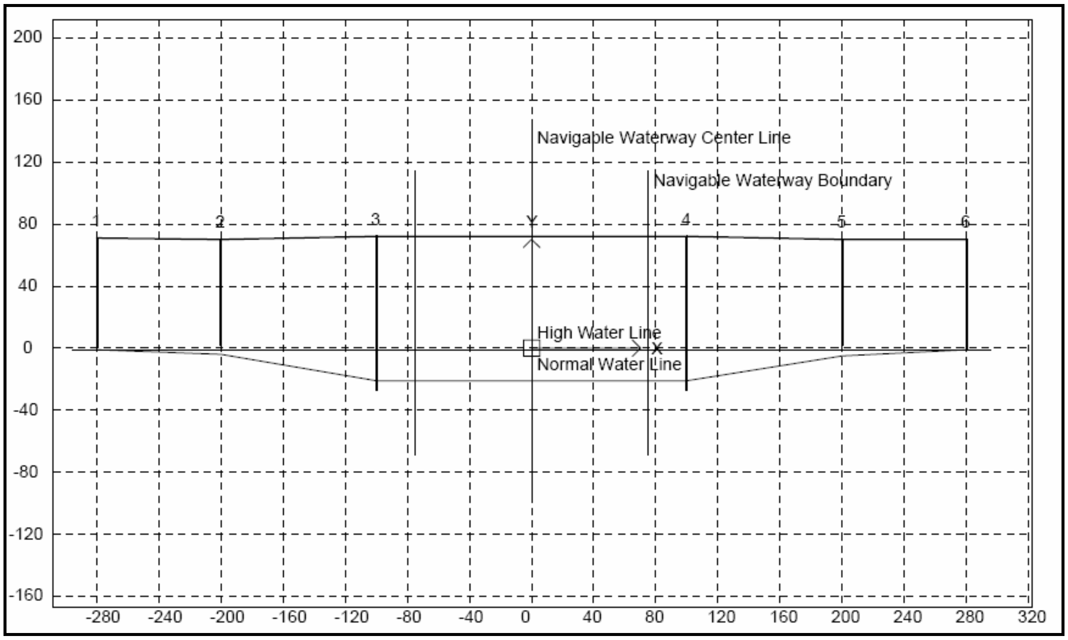


Figure 6-15: GIWW – PR 22 Bridge Geometry

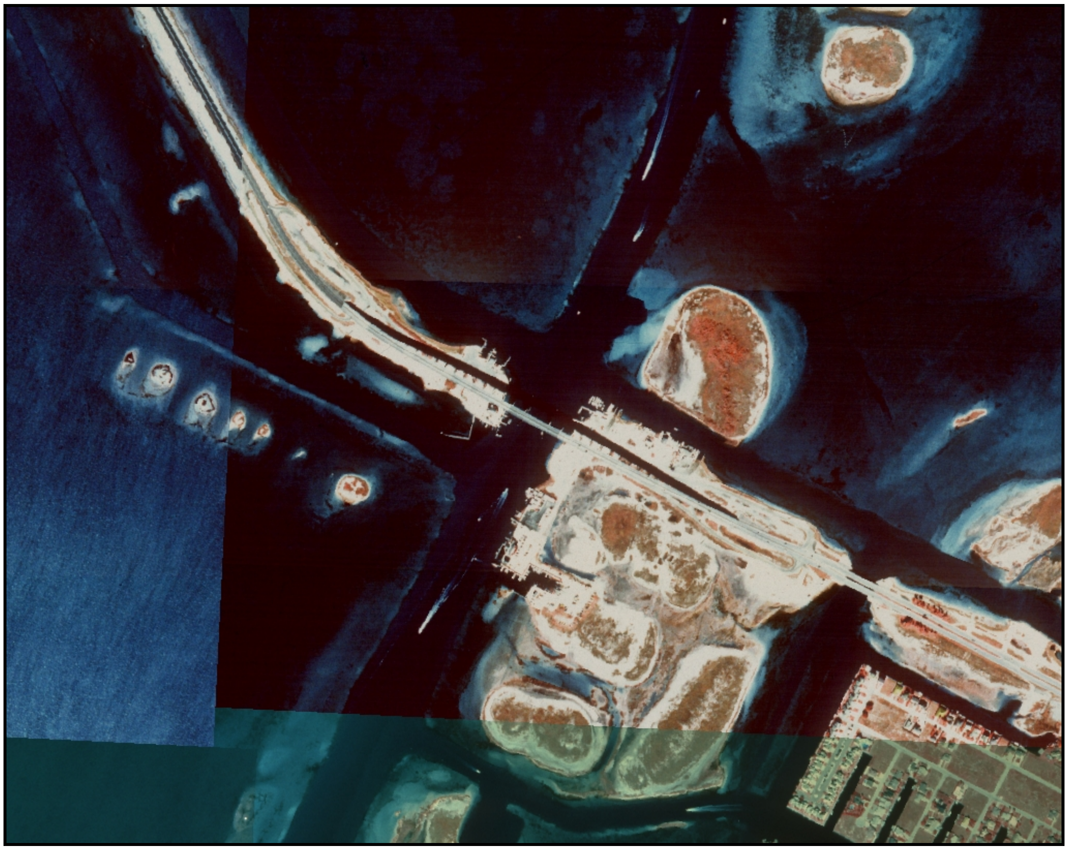


Figure 6-16: Satellite View of the GIWW – PR 22 Bridge and the Surrounding Region of Interest.

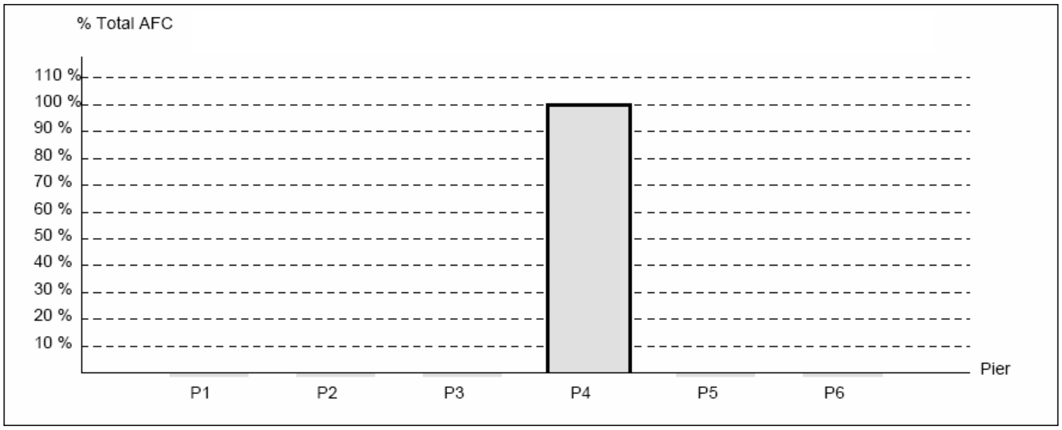


Figure 6-17: Contribution towards the annual frequencies of collapse of all vessels passing a particular pier of the GIWW – PR 22 Bridge (from the VIOB Report)

Vessel i - Pier j	N	PA	PG	PC	AFC
Vessel 1 - Pier 1	1008	0.000251	0.028043	0	0
Vessel 1 - Pier 2	1008	0.000251	0.031204	0	0
Vessel 1 - Pier 3	1008	0.000251	0.041323	0	0
Vessel 1 - Pier 4	1008	0.000251	0.041323	0.002633	0.000028
Vessel 1 - Pier 5	1008	0.000251	0.031204	0	0
Vessel 1 - Pier 6	1008	0.000251	0.028043	0	0
Vessel 2 - Pier 1	288	0.000251	0.021399	0	0
Vessel 2 - Pier 2	288	0.000251	0.022669	0	0
Vessel 2 - Pier 3	288	0.000251	0.02889	0	0
Vessel 2 - Pier 4	288	0.000251	0.02889	0.016654	0.000035
Vessel 2 - Pier 5	288	0.000251	0.022669	0	0
Vessel 2 - Pier 6	288	0.000251	0.021399	0	0
Vessel 3 - Pier 1	144	0.000251	0.017114	0	0
Vessel 3 - Pier 2	144	0.000251	0.017803	0	0
Vessel 3 - Pier 3	144	0.000251	0.02237	0	0
Vessel 3 - Pier 4	144	0.000251	0.02237	0.025842	0.000021
Vessel 3 - Pier 5	144	0.000251	0.017803	0	0
Vessel 3 - Pier 6	144	0.000251	0.017114	0	0
				Total AFC:	**0.000084**

Figure 6-18: Annual frequency of collapse values for each vessel-pier combination for the GIWW – PR 22 Bridge (from the VIOB Report)

It can be seen from Figure 6-17 that only Pier 4 contributes to the annual frequency of collapse of the bridge. Also, it can be seen in Figure 6-18 the reason for this is that the probability of collapse is zero for all of the other piers. The reason the probability of collapse is zero though is not the same for all piers. Pier 3 is at the same distance from the centerline of the navigable channel line as Pier 4, but it has a probability of collapse of zero while Pier 4 has a non-zero probability of collapse. Because the ultimate lateral strength of Pier 4 is 2210 kips and that of Pier 3 is 3900 kips. Figure 6-19 shows the effect that the high pier strength of Pier 3 has on its probability of collapse, causing it to go to zero. The slightly lower pier strength of Pier 4, shown in Figure 6-20, causes the probability of collapse to have a non-zero (though small) value.

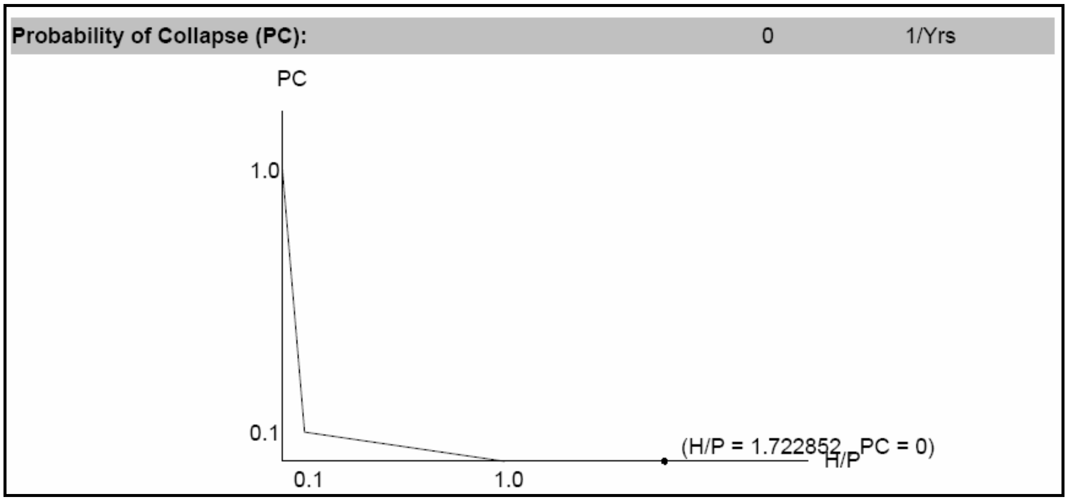


Figure 6-19: Probability of collapse for Vessel 1 Pier 3 for the GIWW – PR 22 Bridge (from the VIOB Report)

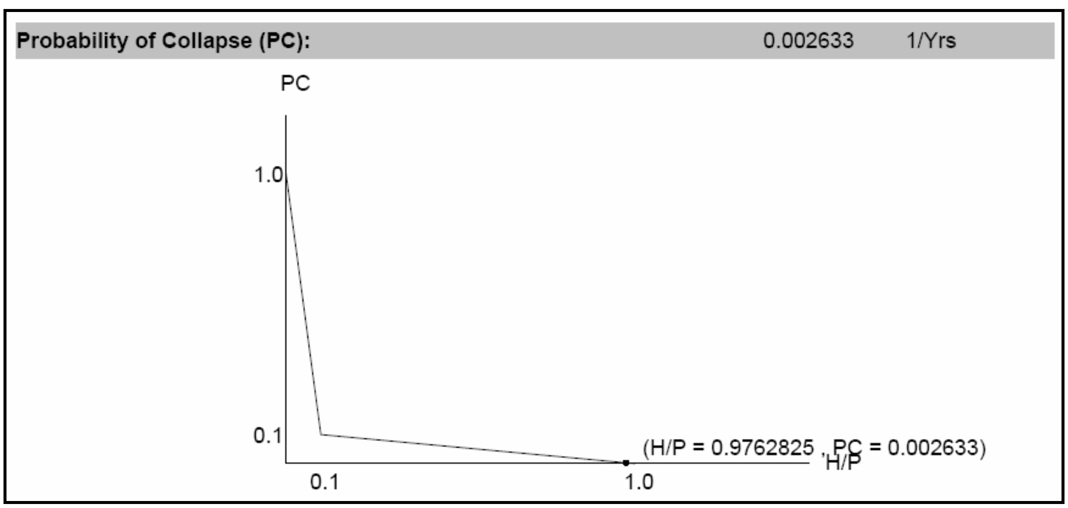


Figure 6-20: Probability of collapse for Vessel 1 Pier 4 for the GIWW – PR 22 Bridge (from the VIOB Report)

While Pier 3's negligible influence on the bridge risk can be explained by its high ultimate lateral pier strength, Piers 1, 2, 5, and 6 cannot be explained similarly. These outer piers all have an ultimate lateral pier strength of 1000 kips, not nearly high enough to drive the probability of collapse to zero. Rather, outer piers have a zero probability of collapse because they are all situated in the very low water depths in the channel. None of the vessels passing this bridge has an underkeel clearance that would allow them to strike any of the four outer piers.

It should also be noted that even though the return period is very high, the probability of collapse of this bridge is still not insignificant. If this bridge were still in the design stage, it might be beneficial to increase the ultimate lateral strength of Pier 4 so that it too has a negligible probability of collapse. If this were done, the bridge would effectively have an almost infinite return period. Often, an infinite return period is optimal when future vessel traffic is difficult to predict or when trends suggest rapid growth in traffic.

CHAPTER 7

VIOB: The Next Generation of Analysis for Vessel Impact on Bridges

7.1 VIOB Introduction

If one considers computational effort involved in just one annual frequency of collapse calculation, for just one type of vessel passing one pier of one bridge, there can be upwards of 100 calculations depending on the type of vessel. If one then assumes a modest number of different vessels, say five, and an average number of bridge piers, say four, then over 2000 calculations would be required for each bridge to determine the total annual frequency of collapse. Due to the large number of calculations needed to determine the return period of a bridge, it is necessary to create an automated solution to the problem.

7.1.1 Past Vessel Impact Analysis Tools

The Florida Department of Transportation (FDOT) has made available a Mathcad spreadsheet which can be used to determine the annual frequency of collapse of a bridge on a Florida waterway using the AASHTO LRFD specifications. While FDOT's spreadsheet can help to perform the desired vessel collision analysis, the program has several limitations. It is not a standalone program, the data are Florida-specific, it is difficult to change, it allows only one type of analysis, it does not give a comprehensive output, and it does not allow the user to create reports summarizing salient details of the analysis.

Several problems arise because the Florida Mathcad program is not a standalone program. This can be a minor or major inconvenience depending on the severity of the version changes. Backward compatibility issues with different versions of Mathcad arise sometimes. The spreadsheet is not logically organized in many places, and this problem is exacerbated when the user tries to make modifications. The layout of the fields on a page makes it virtually impossible to print the spreadsheet without having stray fields sometimes print on a sheet of their own. While the user can spend time trying to create an acceptable format for printing, that time may be better spent analyzing the results.

7.1.2 The Program VIOB and its Features

VIOB is a completely standalone program that reads data from a standard Microsoft Access database and carries out all of the analysis required to evaluate bridges against vessel impact according to the AASHTO LRFD code. It was developed as part of this research study that is reported in this thesis.

The straightforward approach of VIOB and its conveniently designed user interface allow the user to easily insert necessary data and perform calculations using the data. Modifying the database is extremely simple as the vessel libraries provide quick viewing and retrieval of data. Most importantly, the enhanced graphical capabilities of VIOB make trouble shooting complicated geometric problems a mundane task. Finally, comprehensive reports can be produced and the output allows clear understanding and insights into the results as was seen in Chapter 6.

7.2 USER FLOW CHART

Figure 7-1 shows a flow chart of the steps that a user would take to analyze a bridge in VIOB. This rest of this chapter provides a detailed explanation of each of the features of VIOB. For a step-by-step example see Appendix B.

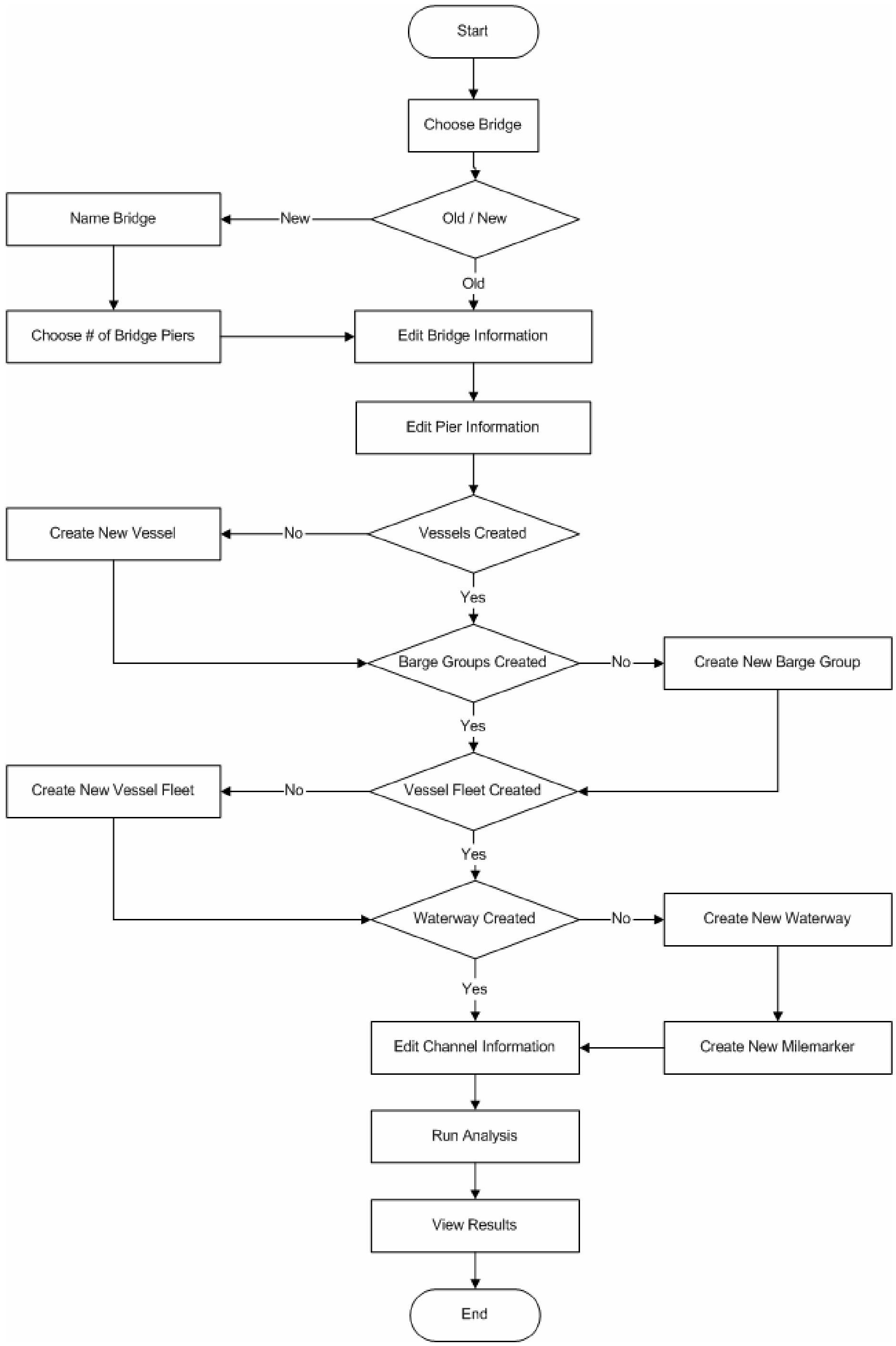


Figure 7-1: User Flow Chart for Analysis of a Single Bridge in VIOB

7.3 DESCRIPTION OF THE PROGRAM

Like most analysis programs, VIOB consists of three parts: a preprocessing component, a solver component, and a post processing component. Each stage of the program performs different functions and involves different relative amounts of user work and computer work.

7.3.1 Preprocessor

The preprocessor stage of VIOB is where most of the user input occurs. The user inputs all of the data that will be used for the calculations and VIOB takes all of the information that the user enters and stores it in a database until the calculations are run.

7.3.1.1 Start Menu

On first opening the program, the user is greeted by the start menu page, shown in Figure 7-2. On this start menu page, the user has the option to analyze an existing bridge, create a new bridge, or delete an existing bridge.

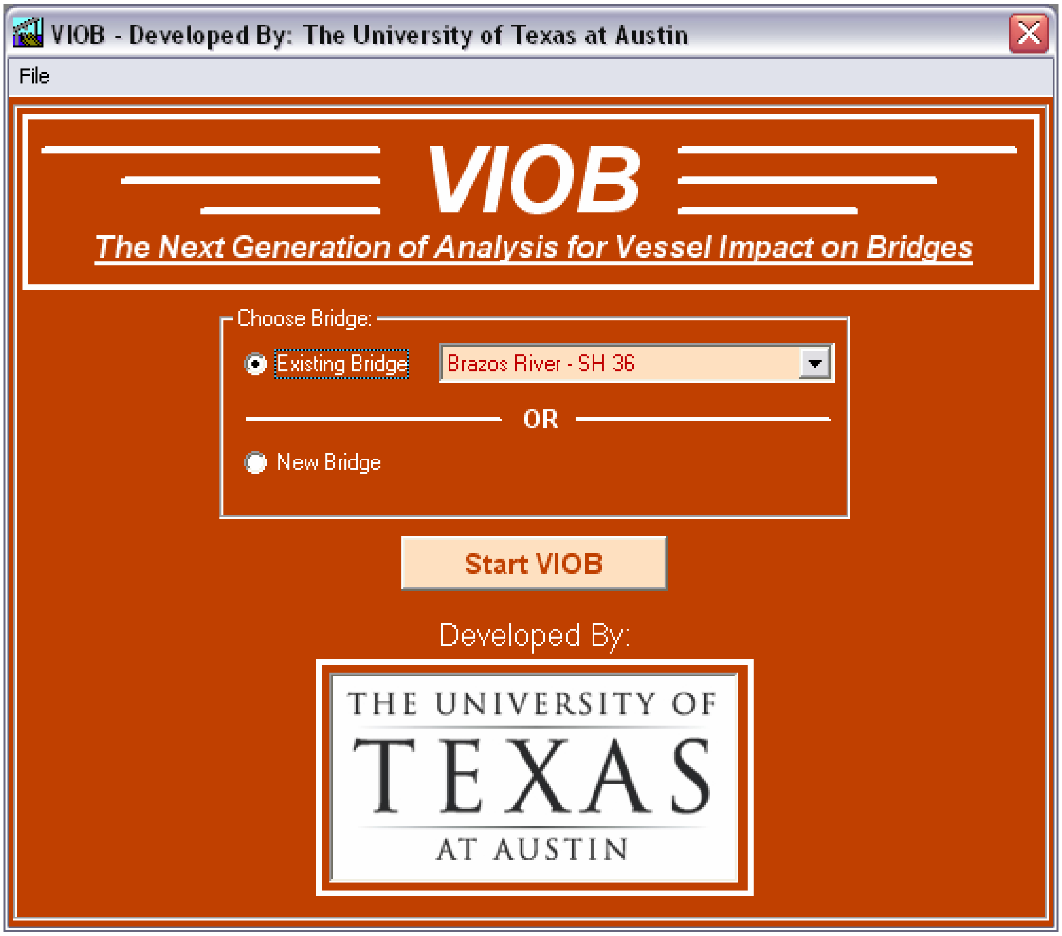


Figure 7-2: Start Menu screen shot

7.3.1.1.1 Work With Existing Bridge

If the objective is to work with an existing bridge, the user must simply select the "Existing Bridge" option button and then select the bridge that he/she wishes wish to use from the pull-down menu. In order to begin working with the bridge, the user then clicks the "Start VIOB" button.

7.3.1.1.2 Create New Bridge

If the user wants to create a new bridge, he/she selects the “New Bridge” option and the clicks the “Start VIOB” button to enter information about the new bridge. The new bridge form, shown in Figure 7-3, will pop up and the user is asked to enter information about the bridge he/she wishes to create. The user must enter the waterway which the bridge crosses, the roadway that the bridge is part of, the TxDOT Structure ID of the bridge, the number of piers that the bridge has, and the unit system with which the user wishes to work.

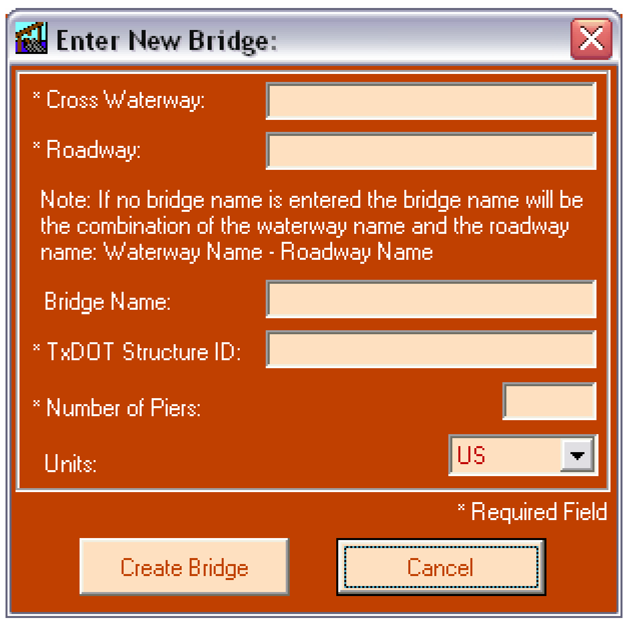


Figure 7-3: New Bridge Screen Shot

If the user does not enter a bridge name, a name will be created from the Cross Waterway and the Roadway in the form: Waterway Name – Roadway Name. In some cases such as with the Queen Isabella Causeway Bridge, an actual name for the bridge exists so the user has the option to enter that. The TxDOT Structure ID is a unique number given to the bridge by TxDOT and can be entered at this time. It is not necessary to provide a number that is a given length or even a real number, but something must be entered into the field for the user to be allowed to continue.

The most important number entered at this point in the program is the number of piers that the bridge has. The program will allow the user to enter any number between 1 and 50. However, it is important to realize that for each of these piers, some additional information will need to be entered subsequently. It is not recommended to include piers that are not in the waterway or are extremely far from the centerline of the channel as they will be unnecessary for the calculations and will be mostly wasted effort. Adding extra piers will not make a significant difference in the computation time as the program executes a single analysis nearly instantaneously. It is not possible to change the number of piers in the bridge at a later stage; therefore, the user should make sure to enter this number correctly. Future versions of this program will likely include a feature allowing the user to add or remove piers from the bridge.

The final information added on the New Bridge form is a selection of the unit system that will be used in the computations. There are seven physical quantities for which units are needed; the user can select either the SI or US system of units. The different unit schemes are listed in Table 7-1. In future versions of VIOB, other unit configurations will likely be added. As with the number of piers, the selected unit system may not be changed at a later stage.

Table 7-1: Different unit schemes

Category	US	SI
Length	ft	mm
Mass 1	ton	Mg
Mass 2	tonne	Mg
Velocity 1	knots	km / hr
Velocity 2	ft / s	m / s
Force	kips	N
Energy	kip - ft	J

7.3.1.1.3 Delete an Existing Bridge

To delete an existing bridge the user first goes to the pull-down menu and selects the desired bridge. Next the user goes to the **File > Delete Bridge...** A message box, shown in Figure 7-4, asking the user, "Are you sure you want to delete the bridge: Example Bridge?" pops up on the screen. If the user clicks "Yes" then the bridge is deleted and the user is returned to the Start Menu page. If the user clicks "No" the bridge is not deleted and the user is returned to the Start Menu page.

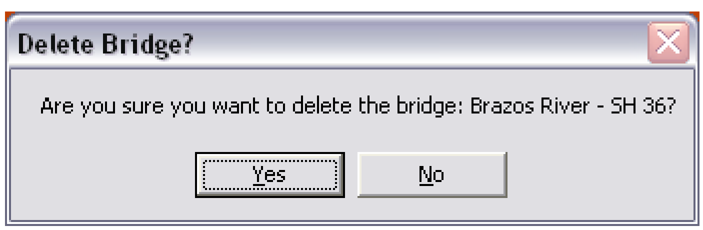


Figure 7-4: Delete Bridge pop-up screen shot

7.3.1.2 Main Page

Once the user has either selected to use an existing bridge or created a new bridge, the start page closes and the main page, shown in Figure 7-5, is presented. The main page has many different features on it including: data display, bridge selection, edit features, plot display, run calculations, and database manipulation. A stick plot based on user-input geometry shows the bridge. In this plot, vessel traffic under the bridge moves into or out of the page and vehicle traffic on the bridge moves from left to right or vise versa.

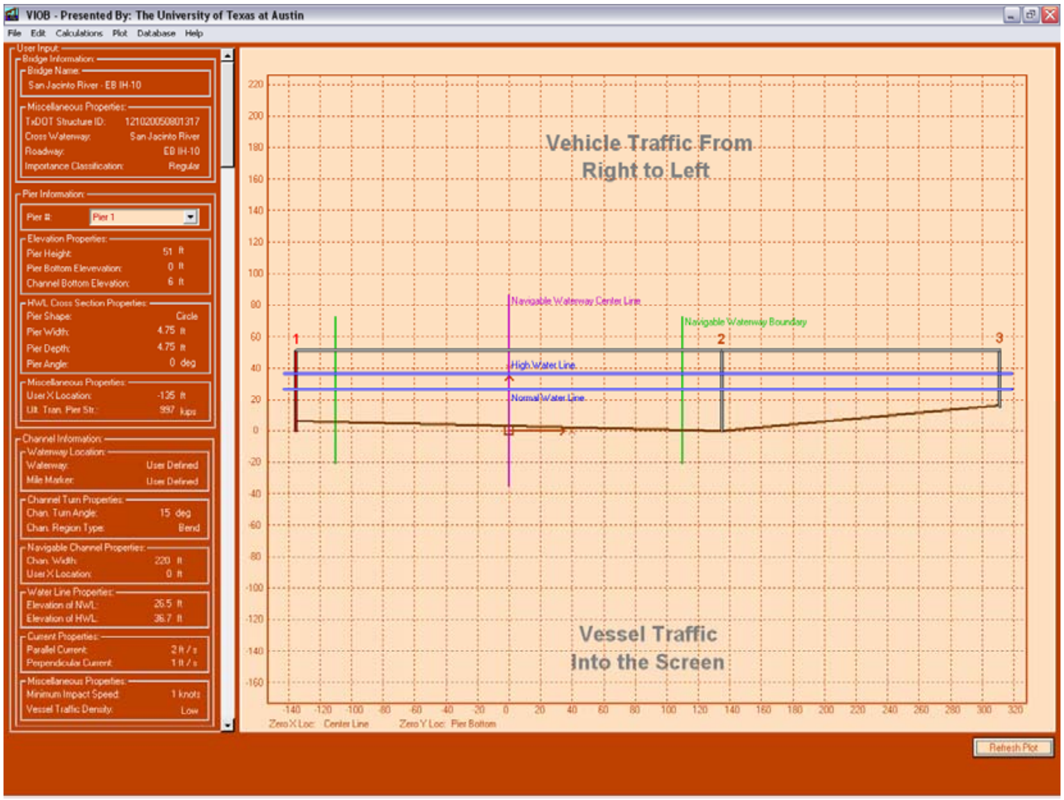


Figure 7-5: Main Page Screen Shot

7.3.1.2.1 Data Display

On the left hand side of the screen, all of the data about the bridge and the channel are displayed so that the user can quickly see this information. By selecting the pier pull-down menu, the user can scroll through the various piers. When a pier is selected, the plotted pier on the right corresponding to the selected pier will be highlighted in red. Numbers appearing above the plotted piers indicate the index number of the pier and this number will also turn red when that pier is selected by the user.

On the lower left hand corner of the plot, the origin x and origin y locations are noted. The location of the origin is also indicated by the origin icon. The location of any point on the plot can be determined quickly by moving the mouse over a point. The coordinates of the point over which the mouse is located will be displayed in the lower right hand corner of the plot display.

7.3.1.2.2 Changing the Origin

The user can change the origin location by clicking on **Plot > Origin Location…** from the Main Page. The user has the ability to change both the X origin location and Y origin location independently (See Figure 7-6). The X origin location can be selected to be at any of the piers or at the centerline of the navigable channel. The Y origin can be selected as the pier bottom, pier top, channel bottom, normal water line or high water line. All of the Y origin locations are associated with Pier 1. So if "Pier Top" is selected, the Y origin will be the top of Pier 1 even if the X origin is located at the centerline of the navigable channel or at a different pier.

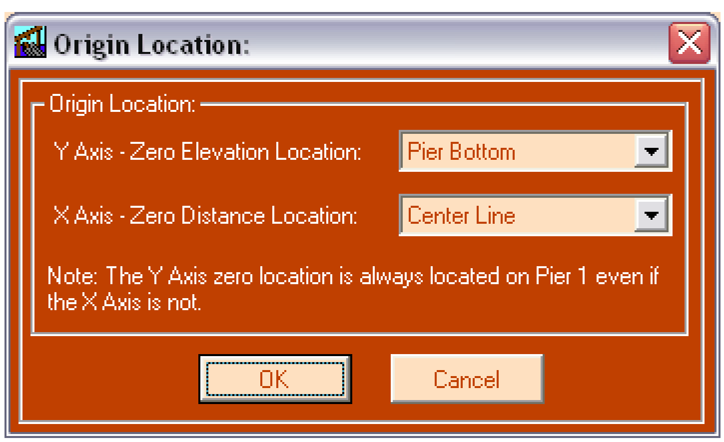


Figure 7-6: Origin Location Screen Shot

The user selects the desired origin from the pull-down menu. Once the user selects a new origin, all of the geometry data are automatically updated with reference to the new origin location.

7.3.1.2.3 Plot Display

On the plot itself, several features are displayed and can be turned on or off. Displayed features include: channel bottom, navigable channel boundaries, navigable channel centerline, piers, bridge deck, traffic direction labels, normal water line, and high water line. All of these features and their labels can be toggled on or off by going to **Plot > Display Options…** That will bring up a Display Options window, shown in Figure 7-7, which allows the user to check which features and labels they would like displayed. The origin and axes can also be toggled on and off in this window.

The user has the ability to change the spacing of the grid lines from the Display Options menu. VIOB offers an Auto Spacing option for both the X and Y grids. If the Auto Spacing feature is turned on, VIOB will automatically space the grid lines in an aesthetically pleasing an optimal manner.

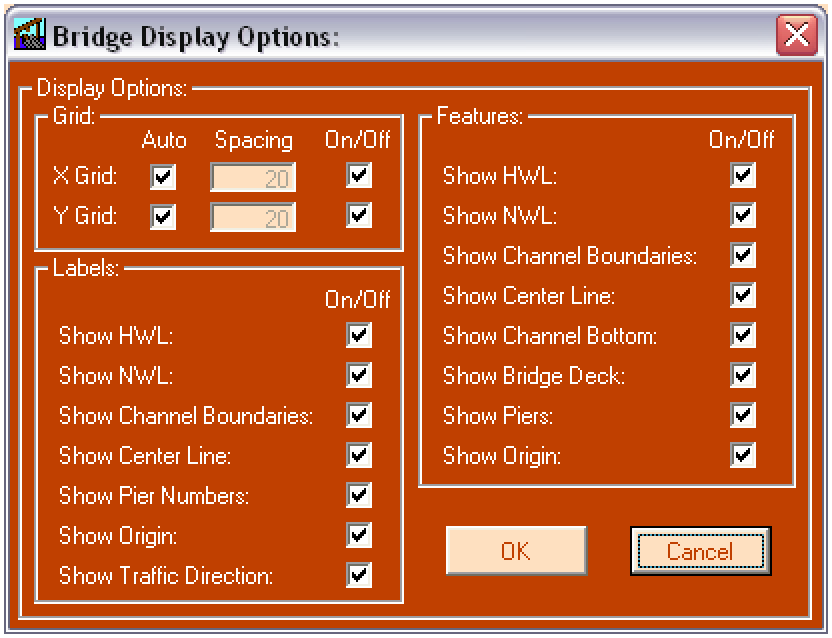


Figure 7-7: Display Options Screen Shot

7.3.1.2.4 Refreshing the Plot

It is possible that the bridge plot will sometimes become "smudged" by other programs or windows that are moved over the bridge plot. In some cases, the plot may even disappear completely. If plot smudging occurs, the user can refresh the plot in two ways. The user can click **Plot** > **Refresh Plot**, or he/she can click the Refresh Plot button in the lower right hand corner of the Main Page window. Both of these actions will restore the plot of the bridge in the Main Page window.

7.3.1.2.5 Switching to a Different Bridge

While the main page currently shows the bridge that was selected on the Start Page, the user may want to switch bridges or start working on a new bridge. The user has bridge-switching capabilities under the **File** menu. In order to start a new bridge, the user goes to **File > New Bridge…** from the Main Page. Choosing the "New Bridge" option will close the Main Page window and reopen the start page window. The "Create New Bridge" option button will already be selected for the user. If the user wants to close the current bridge, he/she clicks on **File > Close Bridge…** If the user chooses the "Close Bridge" option, the Main Page is closed and the Start Page is opened again with the "Select Existing Bridge" option selected. If the user wants to open a different bridge, he/she goes to **File > Open Bridge…** Selecting the "Open Bridge" option has the same effect as selecting the "Close Bridge" option. The Main Page is closed and the Start Page is opened with the "Select Existing Bridge" option pre-selected. Finally, the user can exit VIOB by clicking **File > Exit**.

7.3.1.2.6 Edit Features

Input data is divided into three categories: bridge information, pier information, and channel information. The user can access all three of these features under the **Edit** tab. Further information on these features is provided in Sections 7.3.1.3, 7.3.1.4, and 7.3.1.8.

7.3.1.2.7 Run Calculations

To run calculations the user clicks on **Calculations > Run…** Further information on this feature is provided in Section 7.3.2

7.3.1.2.8 Database Manipulation

All the vessel information is stored in a database and that information is accessed under the **Database** tab. Under the Database tab, the user can edit the Vessel Library, Barge Group Library, Vessel Fleet Library, and the Waterway Library. Further information about each of these databases is provided in Section 7.3.1.6.

7.3.1.3 Edit Bridge Information

To edit bridge information, the user goes to **Edit > Bridge Data…** from the Main Page. This will bring up the “Edit Bridge” window, shown in Figure 7-8, and the user can change several bridge-related variables. The Bridge Name, TxDOT Structure ID, Cross Waterway, Roadway, and Importance Classification are all input in the Edit Bridge window.

Bridge name, cross waterway, and roadway should all have been entered earlier when the user first created the bridge. These values will automatically be displayed when the user opens the Edit Bridge window. As stated earlier, the TxDOT Structure ID is a unique identification number that each structure is given by the Texas Department of Transportation. This number may be in any format the user chooses. If the user does not know the true TxDOT Structure ID, this number a dummy number may be entered instead. The TxDOT Structure ID is not used for any calculations or as a reference in any other part of the program.

Figure 7-8: Edit Bridge Screen Shot

Importance classification is defined in the AASHTO LRFD code Section 3.14.3. The user may enter this value as either "Critical" or "Regular," where the default value is "Regular." The program will later use this importance factor to determine whether the bridge passes the AASHTO LRFD code specifications. Pressing the "OK" button will close the window and save any changes the user made. If the user presses the "Cancel" button, data changes made will not have been saved.

7.3.1.4 Edit Pier Information

To edit individual pier data, the user must click on the **Edit > Pier Data…** tab on the Main Page which will open the "Edit Pier" window, shown in Figure 7-9. The "Edit Pier" window allows the user to edit pier height, pier bottom elevation, channel bottom elevation, cross-sectional properties, x-location, and ultimate transverse pier strength.

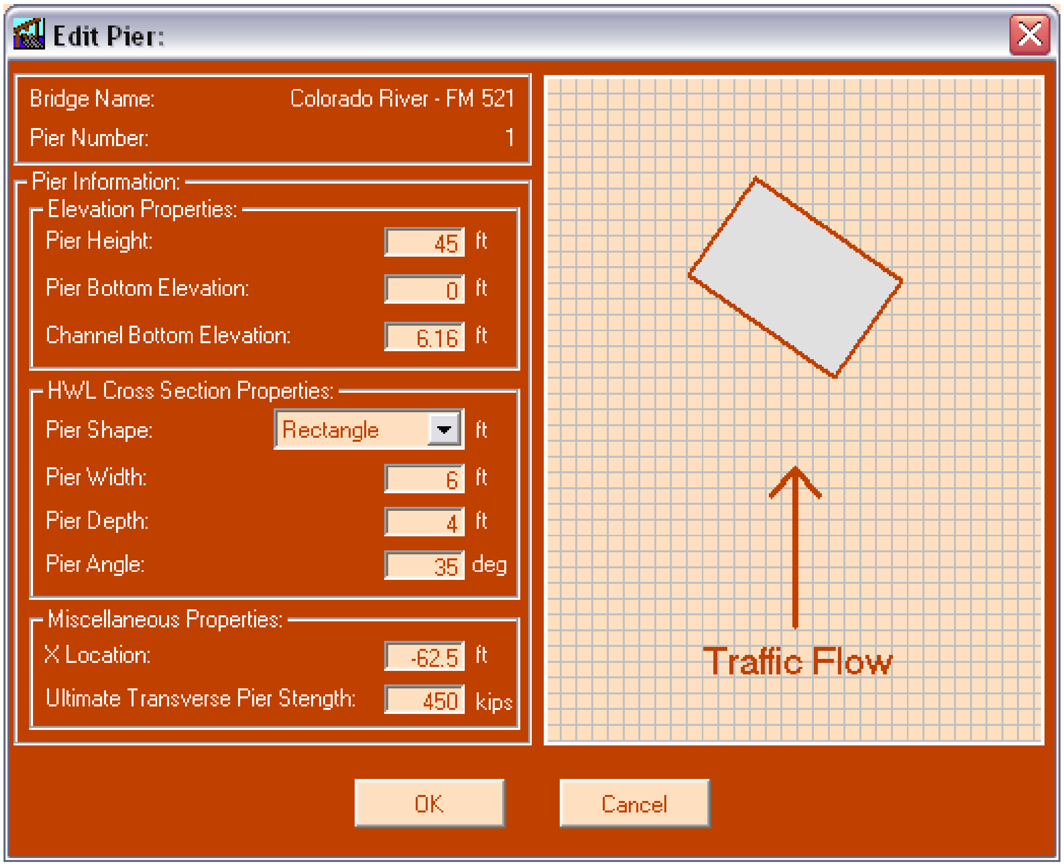


Figure 7-9: Pier Information Screen Shot

The pier height is the distance from the top of the foundation to the bridge deck. This value is not used for the calculations but is used to accurately draw the bridge on the screen. In future versions of the program, this number may be implemented into the calculations so that the height of the bridge deck can be checked to avoid deck collisions. Also, if structural analysis capabilities are integrated into future versions of VIOB, the height of the pier may be important.

Pier bottom elevation is the location of the top of the pier foundation.. Similar to pier height, this value is not used is any calculations. It is only needed so that a relative top of the bridge can be determined for plotting purposes. As pier bottom elevation is associated with deck height, this value would be important for future versions of VIOB for the same reasons as with the pier height value discarded earlier.

Channel bottom elevation is the location of the channel bottom at the same x-location as the pier. It is necessary to know this value in determining the depth of water at the pier. The user can enter channel bottom elevation and water levels and the program will automatically determine what the channel depth is.

The cross-sectional properties of the pier are entered into the program in the "Edit Pier" window. The cross-sectional properties are used to determine B_P, the effective width of the pier if the pier is turned at an angle. This effective width, B_P, is defined in the AASHTO LRFD code section 3.14.5.3 and is indicated in Figure 7-10. To aid the user in entering cross-section properties, the "Edit Pier" form will draw a scaled version of the pier cross-section.

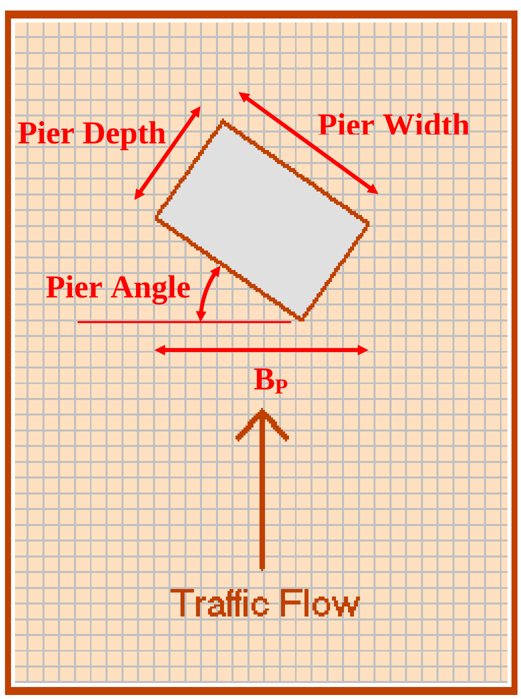


Figure 7-10: Definition of Pier Cross-Sectional Properties

There are four cross-sectional properties necessary for determining B_P. These include the pier shape, width, depth, and angle. Since it is possible that the pier's cross-sectional dimensions can change along its height, the AASHTO LRFD code recommends using the cross-section at the high water line level to represent the worst-case scenario. If the user wants to use a different location, that is possible through data manipulation within VIOB. The program will perform the calculations by using the values entered as high water line values. If the user puts in cross-sectional values at the normal water line and enters the normal water line elevation as the high water line elevation, the program would perform the calculations for these normal water line cross-sectional values.

The user has the ability to enter either a circular or rectangular cross-section into VIOB. For a circular cross-section, the width and depth are equal, and VIOB will automatically make the two values the same. It is also not necessary to enter a pier angle for a circular cross section. For a rectangular cross-section, the pier width, pier depth, and pier angle are defined as shown in Figure 7-10.

In the event that the user wants to enter a cross-section that is neither a circle nor a rectangle, he/she could independently determine the effective width of the pier and enter it as a circular pier with a diameter equal to the effective width of their actual polygonal cross-section.

The x-Location of the pier is the distance in the x direction that the pier is from the origin. The origin is defined by the user on the Main Page, and the user needs to make sure that the x-location entered is appropriate. The program will not permit the user to enter an x-location that would place the piers at a location that is inconsistent in any manner.

Finally, the Ultimate Transverse Pier Strength is entered in the “Edit Pier” window. Defined in AASHTO LRFD code Section 3.14.5.4, the ultimate lateral pier strength is determined by the user outside of VIOB, and then entered into the program at this time. Future versions of VIOB may include a structural analysis component that would perform the calculation for the ultimate pier strength.

7.3.1.5 Edit Channel Information

To edit channel information the user clicks on **Edit > Channel Data…** from the Main Page. The “Edit Channel” page, shown in Figure 7-11, allows the user to edit all information related to the channel such as width, turn angle, region type, navigable channel properties, high water line, normal water line, current velocities, minimum impact speed, and vessel traffic density.

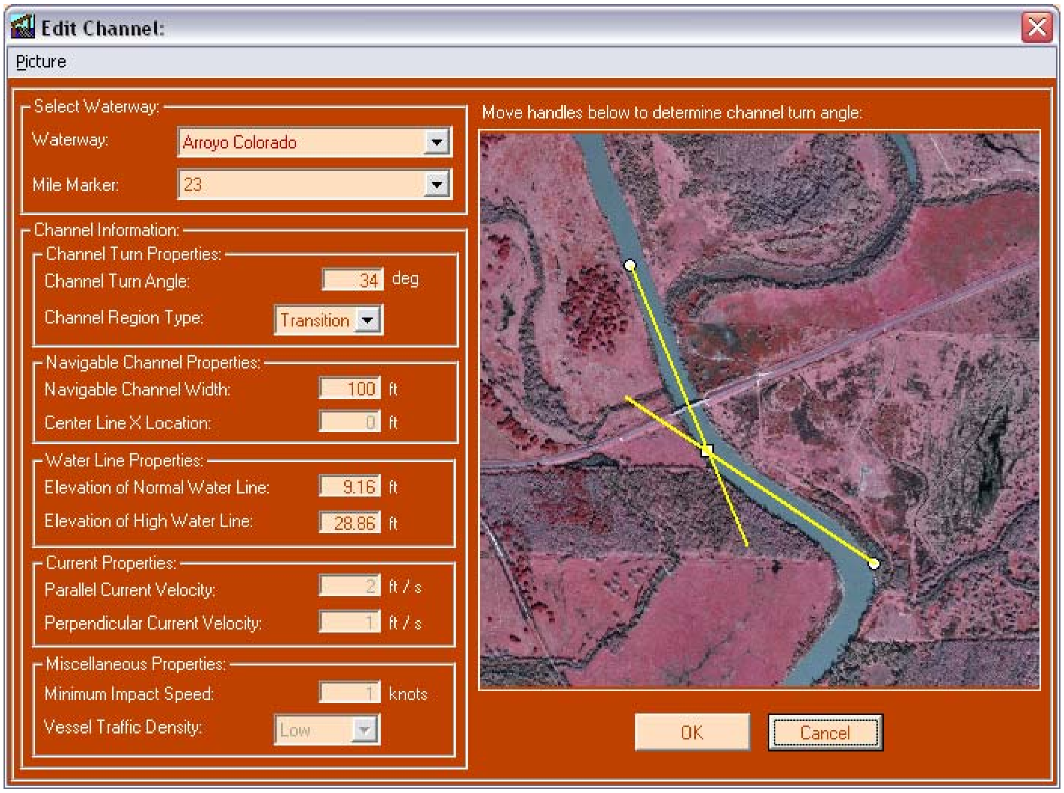


Figure 7-11: Edit Channel Screen Shot

When a bridge is first created, its cross waterway is selected. However, the user will need to select the waterway in the "Edit Channel" window to link the waterway to any given vessel traffic. In the Waterway pull-down menu will be a list of all waterways that are stored in the database. If the waterway does not exist, the user has the option of choosing a "User Defined" waterway, in which case information normally stored in the waterway database and automatically entered for the user is manually entered instead.

Once the user chooses a waterway, the Mile Marker pull-down menu will automatically load with all the mile markers that are stored in the database for the given waterway. Choosing a mile marker automatically fills in parallel current velocity, perpendicular current velocity, minimum impact speed, and vessel traffic density.

The user can determine the channel turn angle in two ways. The first is to measure the channel turn angle by hand, independent of the program, and enter the value into the turn angle box. The second way is for the user to load a picture of the channel into VIOB and use the built-in protractor to determine the turn angle. To load a picture into the VIOB "Edit Channel" window, the user goes to **Picture > Load Picture…** which will bring up a prompt. The user then selects the picture and it will appear beneath a protractor. The user can then move the square handle to adjust the origin of the cross hairs and move the circular handles to rotate the two protractor arms. The turn angle will always indicate the smaller angle between the cross hairs. The turn angle is defined in AASHTO LRFD Section 3.14.5.2.3-1. The turn region, also defined in AASHTO LRFD code Section 3.14.5.2.3-1, can be selected as either straight, transition, turn, or bend.

The navigable waterway is defined as the dredged part of the channel where a given vessel can safely pass under the bridge. The navigable channel width and navigable channel centerline need to be entered by the user.

The high water line and normal water line are both entered by the user and required by VIOB; however, only the high water line is used. The user can enter a dummy number in the normal water line box as that number is not used by the program for any calculations. Entering the correct normal water line can be useful visually as both waterlines are plotted on the Main Page.

The parallel current velocity is the velocity of the current parallel to the vessel traffic, and the perpendicular current velocity is the velocity of the current perpendicular to vessel traffic. If the user chooses a waterway, both current velocities will be automatically entered from the waterway database. Minimum impact speed, also stored in the waterway database, is defined in the AASHTO

LRFD code Section 3.14.6 and must not less than the yearly mean current velocity for the bridge location.

Vessel traffic density is the density level of vessels in the waterway in the immediate vicinity of the bridge. If vessels *rarely* meet or overtake each other the density is considered low. The density is considered average if vessels *occasionally* meet or pass each other. A bridge where vessels *routinely* meet or pass each other would have a density classified as high. VIOB will automatically determine the vessel density correction factor based on AASHTO LRFD code Section 3.14.5.2.3-7, 3-8, and 3-9.

7.3.1.6 Understanding the Vessel Database

7.3.1.6.1 Database Flow Chart

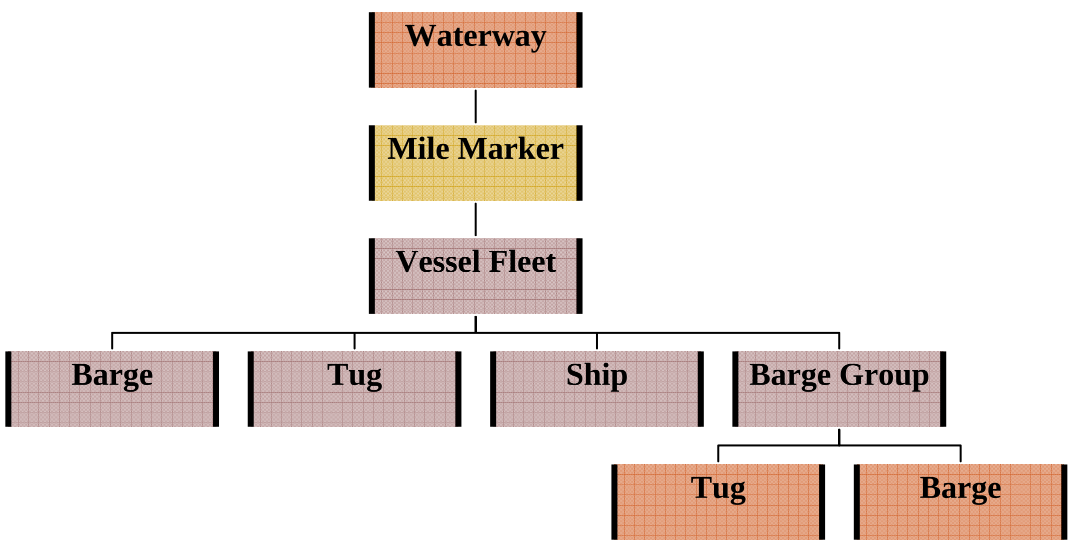


Figure 7-12: Hierarchy of VIOB Database

Figure 7-12 shows the hierarchy of the VIOB database. It is important to understand this hierarchy when working with the VIOB database. The most basic items are vessels. A vessel can be a ship, a tug, or a barge. Each vessel has properties such as length, width and draft. A barge group is a combination of a tug and a series of barges. A barge group can be considered a fourth type of vessel. A vessel fleet is a combination of all vessels that pass under a given bridge. Hence, a vessel fleet is described in terms of a series of vessels that comprise it and the frequency and loading of those vessels as they pass the bridge.

At any given channel location or mile marker, a certain traffic pattern occurs. That traffic pattern is defined by the vessel fleet; hence, each mile marker has a specific vessel fleet that passes it. A waterway is described by a list of all mile markers on its channel. Understanding the terminology that is associated with each type of vessel and vessel group is critical to the user creating and editing the database.

7.3.1.6.2 Vessel Library

The "Vessel Library" is where all of the different barges, tugs, and ships are stored. The user can access the "Vessel Library" by going to **Database > Vessel Library…** from the "Main Page." Once the "Vessel Library" window, shown in Figure 7-13, has been opened, the user has the option to add, edit, or delete barges, tugs, or ships. Data can be entered into the vessel library in either US or SI units; however, all units are stored in the database in US units. An alternative method for populating the database is presented in Appendix A.

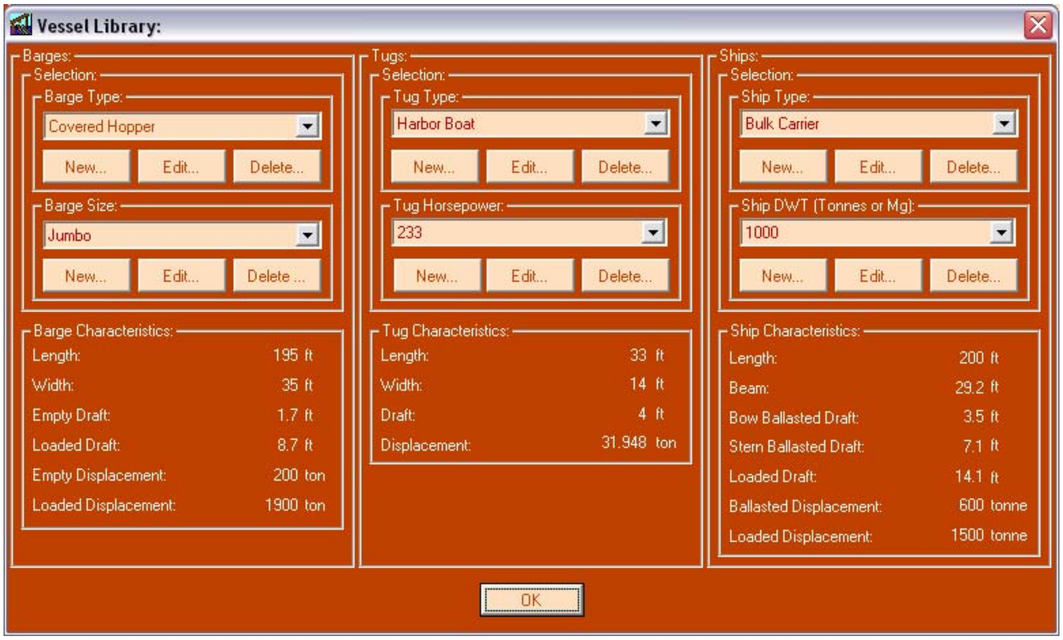


Figure 7-13: Vessel Library Screen Shot

If the user has a bridge opened that is in SI units and enters a new vessel, the input will be assumed to be in SI units as well. VIOB will convert all numbers entered by the user for vessels to US units and store them in the database. The numbers will still be displayed to the user in SI units. This is only the case for vessel data; all bridge and channel data stored in the units in which they are entered.

It is necessary to store vessel data in this manner since the data must be available for all bridges. The user may have opened a bridge and selected US or SI units, and the vessel data should be presented accordingly. Storing the data in two separate databases is another option but it is inconvenient for a user trying to recreate the database outside of VIOB. It is not necessary to perform the same operations fop bridge and channel data because they are unique to a bridge. Once a bridge is created its units cannot be changed; therefore, the data can be stored in any units that it entered in and it will never have to be converted.

7.3.1.6.2.1 Create or Edit Barge

Barges are sorted by Barge Type with a subset for Barge Size. The user has the ability to create a new barge type, edit the barge type or delete the barge type. If the user clicks on the "New…" button in the barge type section, a window, shown in Figure 7-14, will pop up asking the user what the name of the new barge type is.

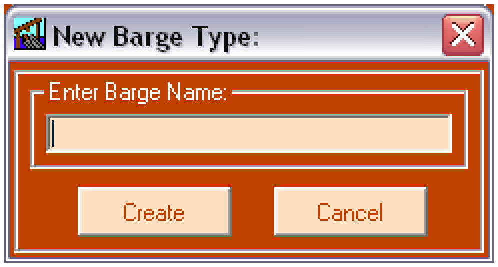


Figure 7-14: New Barge Screen Shot

The user enters the name of the barge type, and the "Barge Dimensions" window, Figure 7-15, will pop up. All barge types must have at least one barge size; therefore, since a new barge type has been created, the user must input the first new barge size. On the "Barge Dimensions" window, the user enters the barge size, length, width, empty draft, loaded draft, empty displacement, and loaded displacement.

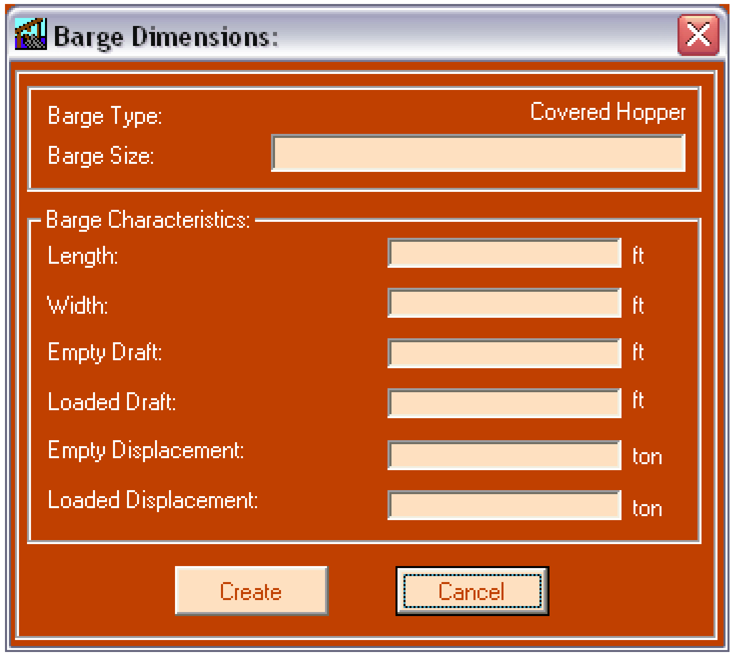


Figure 7-15: New Barge Size Screen Shot

Once the user presses the "Create" button, the new barge type and barge size are added to the vessel library. The user can then add any other barge sizes that are associated with the new barge type by clicking the "New…" button in the barge size box on the "Vessel Library" window. If the user wants to change a barge size there is an option to edit the data. If the user chooses to delete a barge type, all the associated barge sizes will be deleted as well.

7.3.1.6.2.2 Create or Edit a Tug

Creating a tug works in the same way as for a barge as the user has all of the same options with a tug that exist for barges. Tugs are uniquely identified by a type and a horsepower. The horsepower that is entered for the tug is only a label, and the actual value does not matter at all. If the user wants to assign the horsepower as 1 or 9000, it will only serve as a way of distinguishing between different horsepowers for the same type of tugs. When the user clicks on the tug type pull-down menu and selects a type of tug, e.g. "Line Haul," the horsepower pull-down menu is automatically filled with all horsepower tugs that exist for the tug type "Line Haul." The user can create new tug types, edit tug types, and delete tug types. The user can create, edit, and delete tug horsepowers as well. Figure 7-16 shows the window used to enter a new tug name.

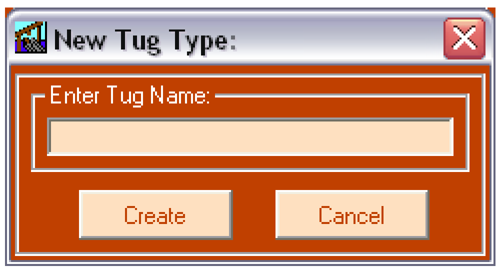


Figure 7-16: New Tug Type Screen Shot

Tug dimensions that need to be entered are length, width, draft, and displacement. Since a tug is never loaded, there is no distinction between loaded and empty draft or loaded and empty displacement. Figure 7-17 shows the window used to enter a new tug horsepower.

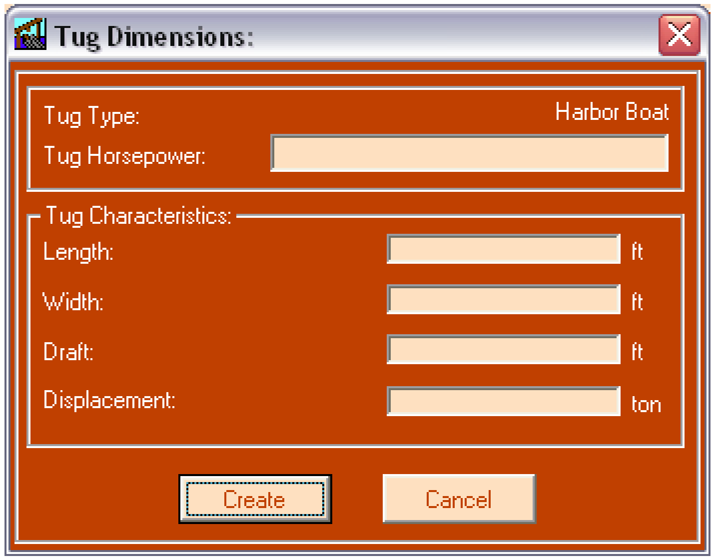


Figure 7-17: New Tug Horsepower Screen Shot

7.3.1.6.2.3 Create or Edit a Ship

As with barges and tugs, the user has the ability to create new ships for the vessel library. Ships are sorted by a two-level system: Type and Dead Weight Tonnage (DWT). Each ship type is comprised of a set of ship DWTs. The user can create, edit, and delete both ship types and ship DWTs. Figure 7-18 shows the window used to edit a ship name.

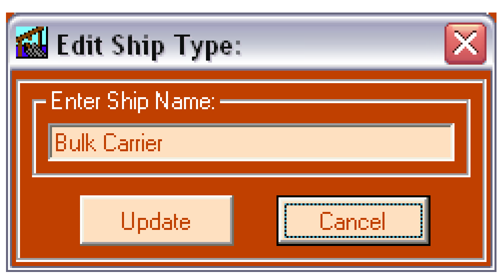


Figure 7-18: Edit Ship Type Screen Shot

For a ship, the user must enter the length, beam, ballasted draft and displacement, and loaded draft and displacement. For the ballasted draft, the user must enter the draft at both the bow and the stern of the ship. The program uses the stern draft as it is larger. The number the user enters for the bow ballasted draft is never used by VIOB. The dead weight tonnage should also be entered accurately as it is used by VIOB in the calculations; DWT is not simply a label as horsepower is for a tug. Figure 7-19 shows the window for entering a new ship DWT.

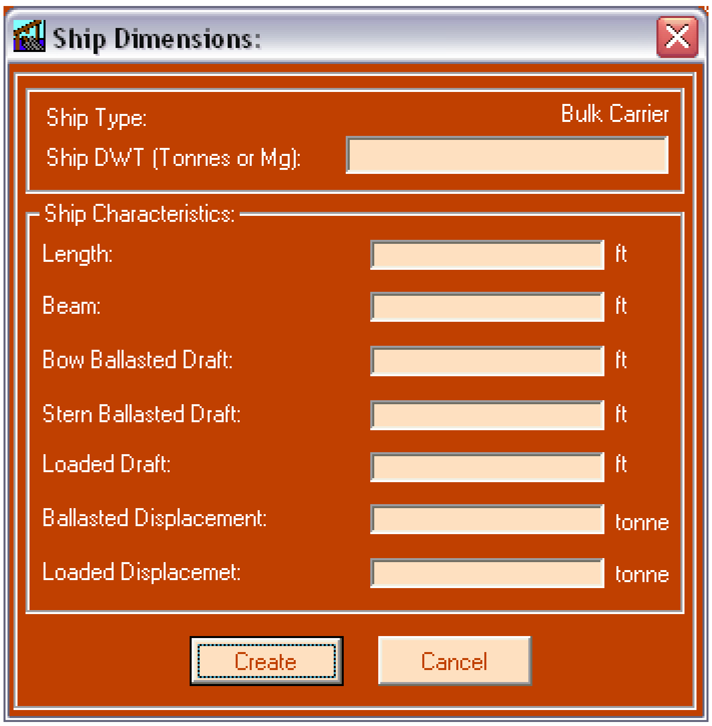


Figure 7-19: New Ship DWT Screen Shot

7.3.1.6.3 Assemble Barge Group

Once the user is satisfied with the vessels in the "Vessel Library," he/she can create barge groups. To work with the "Barge Group Library," the user clicks on **Database > Barge Group Library…** from the "Main Page." This will bring up the "Barge Group Library" window, shown in Figure 7-20. In this window, the user can scroll through different barge groups that have been previously assembled and see what their dimensions are. The user can also create new barge groups or delete existing barge groups.

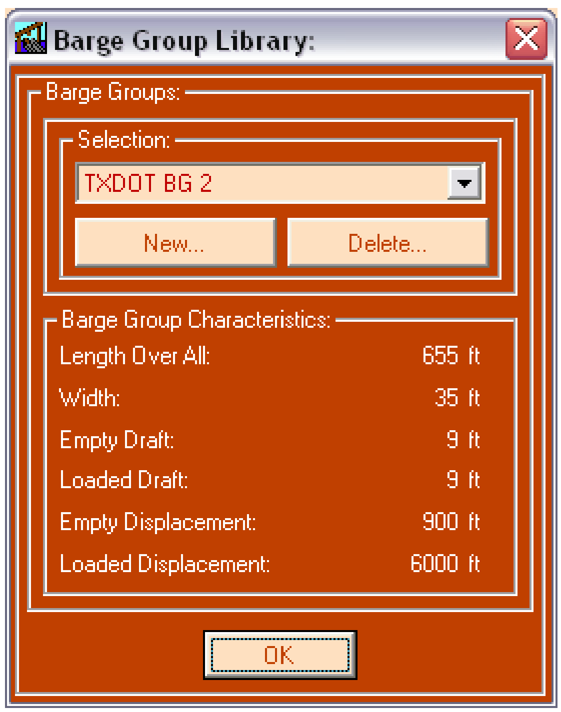


Figure 7-20: Barge Group Library Screen Shot

To create a new barge group, the user clicks on the "New…" button on the "Barge Group Library" window which will open the "Create Barge Group" window. A barge group is an assembly of a set of barges pulled or pushed by a tug. The user can name the barge group as he/she pleases, but it must be a unique name as no two barge groups can have identical names. It is necessary for the user to specify how many barges long and wide the barge group is. For both the number of barges long and the number wide, the user may enter a number between 1 and 10 as long as the total number of barges is less than 24. As the user enters the configuration of barges, VIOB automatically draws a layout of the barge group in the “Create Barge Group” window, shown in Figure 7-21. Seeing a layout of the barge group can help the user ensure that the information entered is appropriate.

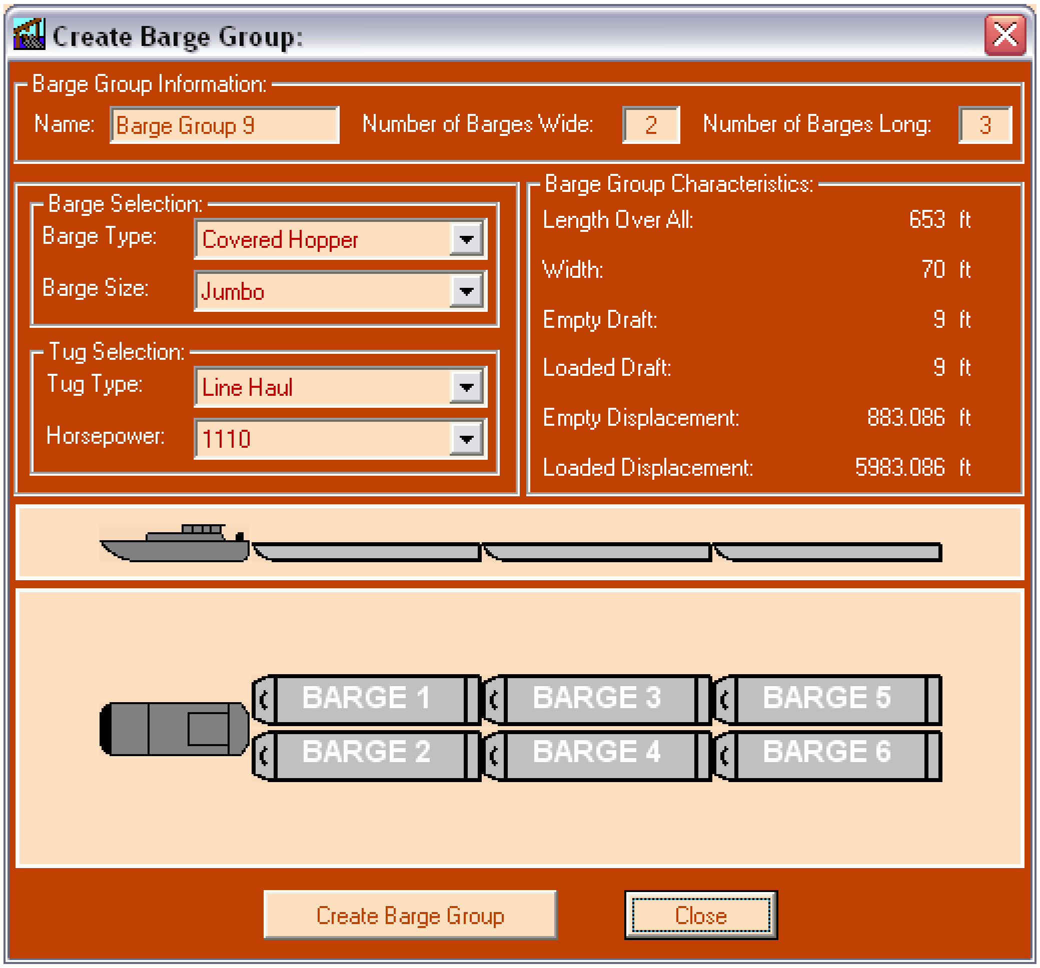


Figure 7-21: Create Barge Group Screen Shot

The user must specify the type and size of barges that are used in the barge group as well as the tug type and tug horsepower is being used in the barge group. The barge group will have only one type of barge. Future versions of VIOB may have a feature in which the user can create a barge group with different barges assembled together. For this version of VIOB, it was decided that only one barge type would be allowed because in practice most barge groups are configured that way and the data input is greatly simplified. As the user picks which tug and barge type will be used, the “Create Barge Group” window will update the statistics for the barge group on the screen. Again, seeing real-time statistics of the barge group characteristics can assure the user that the barge group is assembled as desired.

Once the user has the appropriate information entered into the “Create Barge Group” window, pressing the “Create Barge Group” button will save the barge group to the database. The “Create Barge Group” window will reset itself upon clicking the “Create Barge Group” button, and the user can enter other barge groups. Once the user has created all of the desired barge groups, pressing the “Close” button will close the “Create Barge Group” window and the user will be brought back to the “Barge Group Library.”

7.3.1.6.4 Create Vessel Fleet

With the vessels and barge groups stored in the libraries, the user can now create the vessel fleet. To create a vessel fleet, the user clicks on **Database > Vessel Fleet Library…** from the “Main Page.” This will open the “Vessel Fleet Library” window, shown in Figure 7-22. The “Vessel Fleet Library” window has a pull-down menu with all the vessel fleets that are stored in the database. If the user selects one of these vessel fleets, all of the vessels which make up the vessel fleet will be displayed on the “Vessel Fleet Library” window. The window also shows the vessel’s frequency, loading, and velocity. For the first time, the user is introduced to the term “vessel class.” Vessel class simply refers to the kind of vessel that is being displayed: barge, tug, ship, or barge group. A barge group does not have a vessel size; so, if it is displayed, its vessel size will be “N/A.”

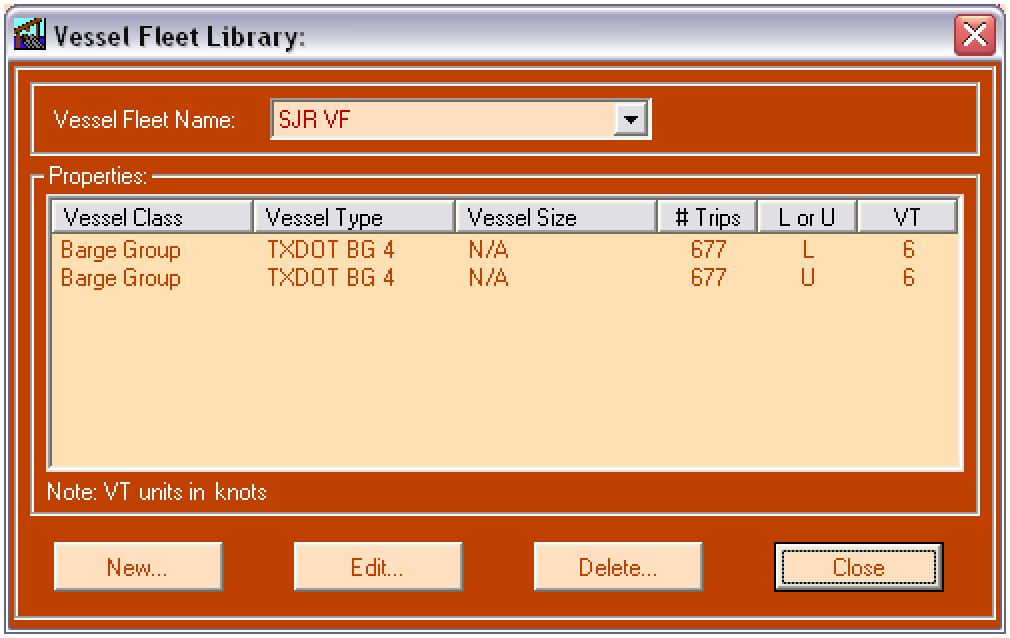


Figure 7-22: Vessel Fleet Library Screen Shot

As with all of the other libraries, the user has the ability to work with the "Vessel Fleet Library." The user can create a new vessel fleet, edit an existing vessel fleet, or delete a vessel fleet. When finished with the "Vessel Fleet Library," clicking the "Close" button returns the user to the "Main Page."

If the user clicks on the "New…" button the "Create Vessel Fleet" window, shown in Figure 7-23, will appear. The user must name the new vessel fleet with a unique name because no two vessel fleets can have the same name. Also to be entered in the "Create New Vessel Fleet" window are the vessels (that will be part of the vessel fleet) and information about each vessel. For each vessel, the user must specify its class, type, size, frequency, loading configuration, and velocity.

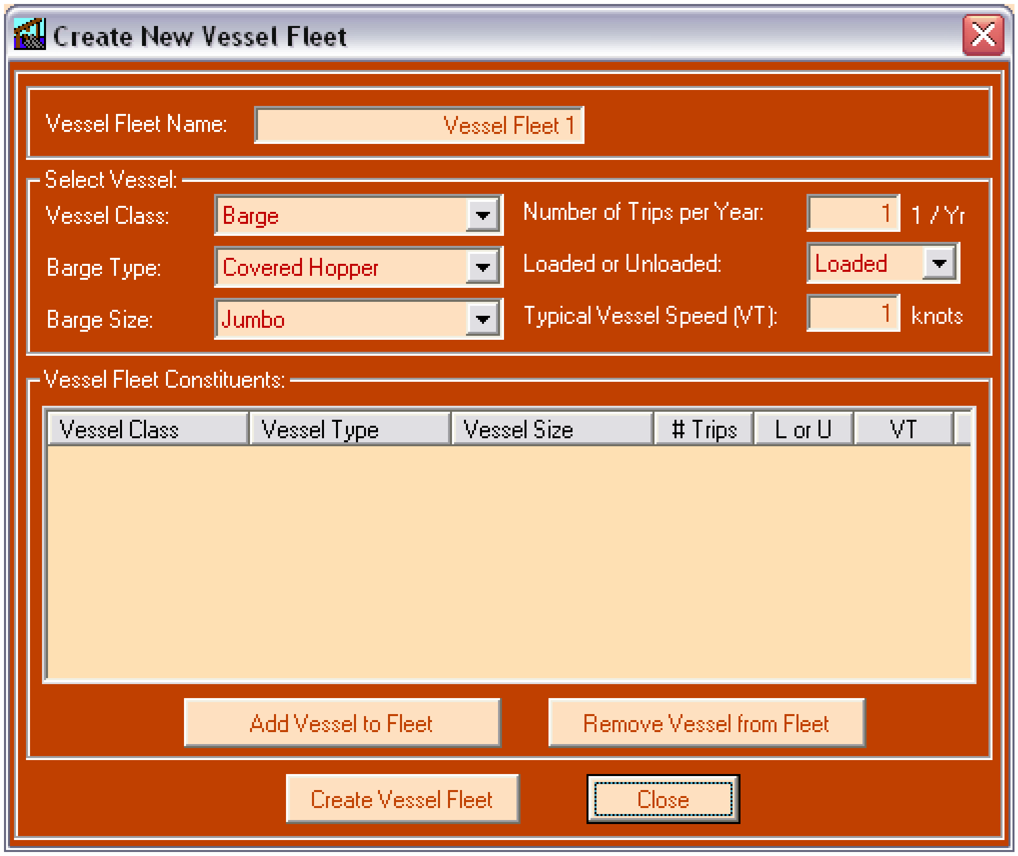


Figure 7-23: Create New Vessel Fleet Form

When the user selects the vessel class from the vessel class pull-down menu, the type and size pull-down menus will automatically reload. If "barge" is selected, the user can select a barge type and barge size; if "tug" is selected, the user can select tug type and tug horsepower; and if "ship" is selected, the user can choose a ship type and ship DWT. The user can also select "barge group" from the vessel class pull-down menu; in this case, the user only needs to select the barge group type.

Once the user has selected the vessel he/she wants to add to the vessel fleet, information about that vessel's traffic pattern needs to be input. The user must specify the number of trips per year that the vessel makes past a given location, whether the vessel is loaded or unloaded during those trips, and what velocity the vessel has during each passage. If a vessel is sometimes loaded and sometimes unloaded, the user should add the vessel to the vessel fleet twice, once with "loaded" selected and once with "unloaded" selected. Each time the vessel is added, the number of trips for each loading and speed configuration is added with it.

To add the vessel to the vessel fleet, the "Add Vessel to Fleet" button is clicked. The vessel information entered by the user will be transferred to the viewing window and the input boxes will be reset. The user can remove a vessel from the fleet by clicking the "Remove Vessel from Fleet" button. When all of the vessels the user wants in the vessel fleet have been added, the user clicks the "Create Vessel Fleet" button to create the vessel fleet.

7.3.1.6.5 Create Waterway

Now that the user has created a vessel fleet, it is necessary to place that vessel fleet at a given mile marker on a waterway. At a given mile marker of a waterway, there are specific channel characteristics and traffic patterns. The user has already created the traffic patterns; now it is necessary to assign them to the mile marker. To do this, the user clicks on **Database** > **Waterway Library…** from the "Main Page." The "Waterway Library" window, shown in Figure 7-24, will pop up. The user has the ability to create a waterway and any mile markers that are a part of that waterway. For any waterway and mile marker that is selected, information about that location is displayed in the window.

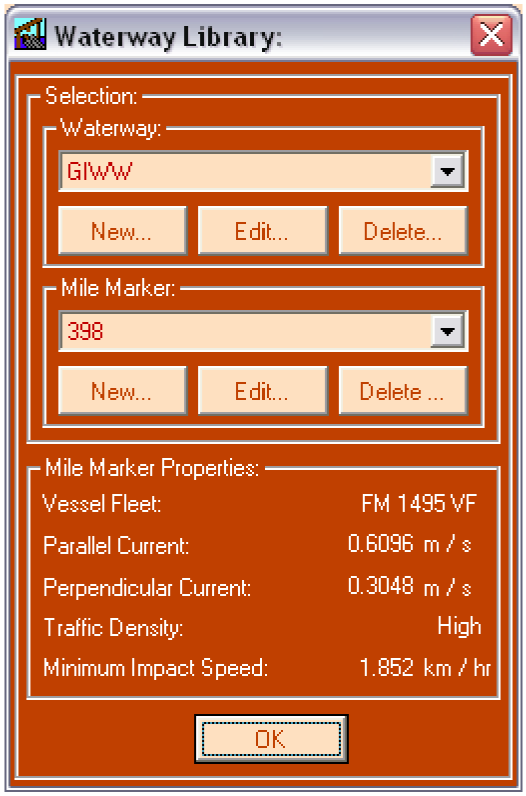


Figure 7-24: Waterway Library Screen Shot

To add a new waterway, the user clicks the "New…" button under the waterway category on the "Waterway Library" window. Once the user creates the waterway he/she will have the opportunity to add mile markers to it.

7.3.1.6.6 Create Mile Marker

If the user clicks the new mile marker button on the "Waterway Library" window, a window allowing the user to input information about that waterway will pop up, as seen Figure 7-25. The same window (only with data in it) will pop up if the user clicks the Edit Mile Marker button. When the "Edit Mile Marker" window opens, the user must enter several key statistics about the mile marker.

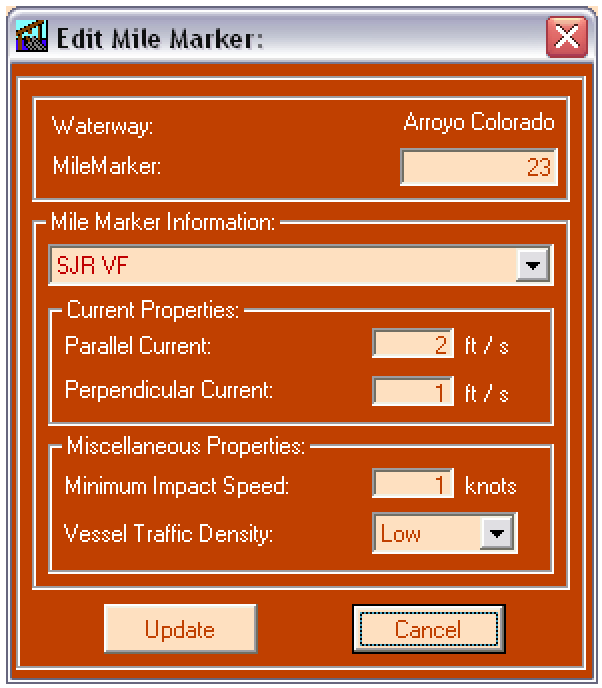


Figure 7-25: Edit Mile Marker Screen Shot

The user must link a vessel fleet to the mile marker and enter the parallel and perpendicular currents, the traffic density, and the minimum impact speed. When the user edits channel data at a later time and links the channel to a specific waterway and mile marker all of the data entered for the mile marker is automatically entered into the "Edit Channel" window.

7.3.2 Solver

The solver part of VIOB is where all of the calculations are performed. In the code, all of the calculation procedures are located in the "RunAnlaysisCalcs" module. If at any time modifications are made to the AASHTO LRFD code or a new calculation is formulated, adjustments to the VIOB solver should be made in this module. Each separate calculation is performed as its own function; so functions can be easily swapped in and out to reflect updates to the AASTHO LRFD specifications.

7.3.2.1 Run Analysis

With all of the data entered into VIOB, the user can now begin the calculations. To run the analyses, the user clicks on **Calculations > Run…** from the "Main page." This will bring up the "Analysis Wizard" window where the user can enter a few key pieces of information and determine if the bridge is acceptable based on its reurn period associated with collapse due to vessel impact.

In the "Analysis Wizard" window, shown in Figure 7-26, the only piece of information the user must enter is his/her name. All the other pieces of information will be selected automatically. However, the user can change some of the selections that VIOB has pre-selected. The growth factor that the program uses for vessel frequency is input here; the default value is 1.2. The growth factor accounts for possible increases in vessel traffic in future years. Using a value of 1.2 for the growth factor is conservative, but it is important to use a growth factor as vessel traffic is always changing. If the user wants to use a less conservative value, they can change that value at this point.

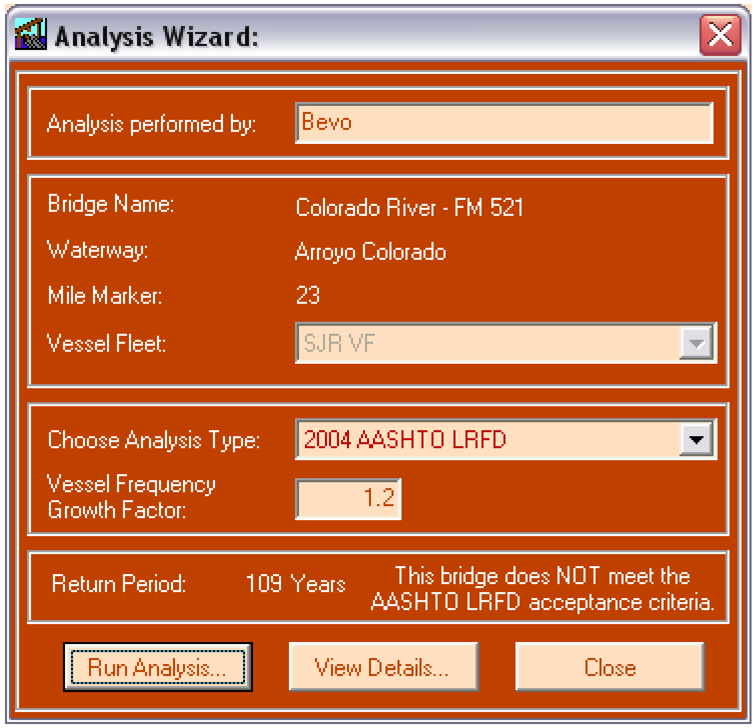


Figure 7-26: Analysis Wizard Screen Shot

If the user selected a user-defined waterway in the "Edit Channel" window, then the vessel fleet that passes the bridge of choice will not be known. If that is the case, then the vessel fleet pull-down menu will not be disabled and the user will pick the appropriate vessel fleet. If the user had already selected the waterway and mile marker, VIOB automatically chooses the correct vessel fleet.

Analysis Type only offers two options, "2004 AASHTO LRFD" and "2005 University of Texas," each with its own assumptions. The "2004 AASHTO LRFD" analysis is exactly the analysis in the 2004 AASHTO LRFD code, and it will yield the same results as the Guide Specifications. The 2005 University of Texas method is based on an alternative approach for computing the probability of collapse as outlined in Chapter 4. This is under development. In the future, additional methods of analysis could be added to the program and selected here.

Once the user has selected all of the options that are desired for the calculation, the final step is to click the "Run Analysis…" button on the "Analysis Wizard" page. This will run the VIOB analysis and yield a result almost instantaneously. The return period and Pass/Fail message will be displayed on the "Analysis Wizard" window. Once the analysis has been run, the "View Details" button will be enabled and the user will have the option to look at details in the VIOB calculations.

7.3.3 Postprocessor

The post-processing section of VIOB allows the user to study the results graphically and manipulate it in different ways for interpretation. Having advanced post-processing features makes the results easier to review than is possible with only numerical summaries. Indeed, the various output formats provide useful insights into factors that influence the frequency of bridge collapses. VIOB has numerous advanced post-processing features that help the user make an educated data-supported decision about the best way to increase the return period associated with bridge collapses.

7.3.3.1 View Detailed Results

When the user clicks the "View Details…" button from the "Analysis Wizard" window the "Results Viewer" window, shown in Figure 7-27, appears. Results are split up into several categories and the user can review them in several different ways. In the upper left hand corner of the "Results Viewer" window is basic information including the bridge name, vessel fleet, waterway, mile marker, analysis type, and waterway. To the right of the basic information is a box that including summary results such as the annual frequency of collapse, return period, importance classification, and whether or not the bridge passes the AASHTO LRFD code specifications.

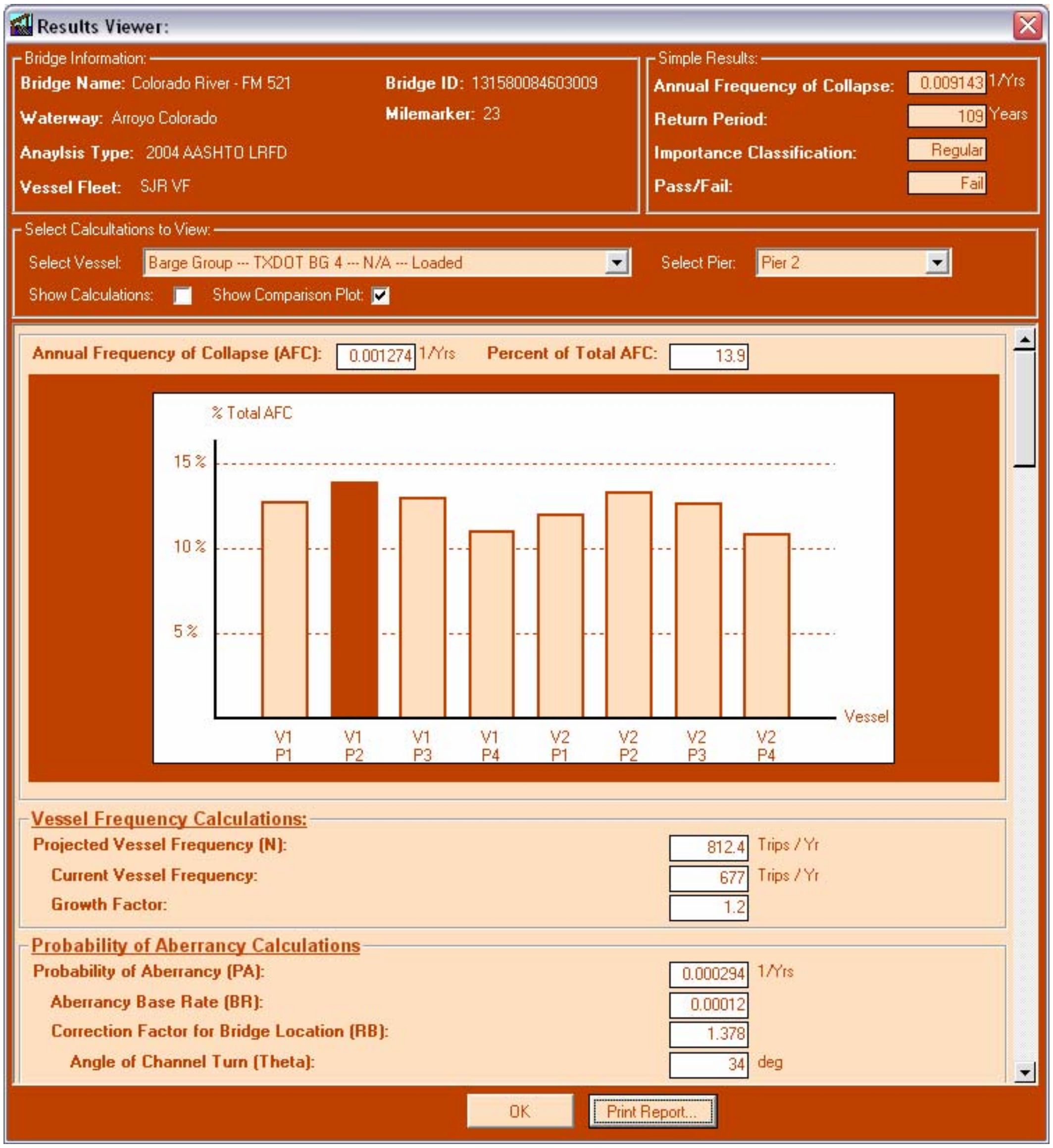


Figure 7-27: Results Viewer Screen Shot

The user may want to see more detailed information about how each calculation is performed. For any vessel impact analysis, a separate calculation is performed for every vessel-pier combination. Therefore, if there are four piers and three vessels, twelve separate calculations of annual frequency of collapse are performed, and the results are then summed to get the total annual frequency of collapse. The user can select any vessel-pier combination on the "Results Viewer" window, and details about that calculation will appear. The user can also select all piers with a given vessel, or all vessels with a given pier, and see how much one specific pier or one specific vessel influences the overall frequency of bridge collapse.

Beneath the box where the user selects the vessel and pier that they want to review, are the actual values used by VIOB. It is important that VIOB display these numbers so that the user can ensure that the numbers were entered properly and that they seem reasonable. Every single number used in all of the calculations can be reviewed if necessary. The results are split into categories of vessel frequency, probability of aberrancy, geometric probability, and probability of collapse.

If the user clicks on a specific pier and a specific vessel, all of the numbers used for that specific calculation are displayed. However, if the user selects all vessels for a specific pier or all piers for a specific vessel, some of the variables will be displayed as dashes. This is because in the group modes, only variables that are common to all runs for that group can be shown. For instance, pier height will be shown if all vessels for Pier 2 are requested. The height of Pier 2 does not change for any of the calculations in that group. On the other hand, if the same group is requested, vessel length will not be shown, because each of the vessels potentially has a different length; therefore, VIOB displays that variable as "-."

The variables are all grouped together by indents. So variables indented under another variable are used for computation of that variable. This way the user can tell which variables are used to get any specific results. This is also helpful when reviewing the calculations/results.

7.3.3.2 View Calculations

One very unique feature of VIOB is that it will display every calculation that was made in equation form. This is a useful way to check the results numerically and to read them in a standard way as opposed to from an excessively long table. To view the calculations, the user clicks the check box "Show Calculations" on the "Results Viewer" window. This will cause the window to reassemble itself and all of the calculations and plots used to determine the annual frequency of collapse will be displayed. Each calculation shows the equation that was used and beneath that the equation with actual numbers plugged in.

Three plots are also visible when the calculations are shown: the first shows the normal distribution curve used for calculating geometric probability; the second shows the method for determining velocity; and the third shows the formulation of the probability of collapse computation. Each of these plots shows actual points corresponding to the analysis completed.

7.3.3.3 Compare Results

Finally, the user can compare different vessel-pier combinations with each other to see which ones have the influence on the total annual frequency of collapse. To review this analysis, the user clicks on the check box labeled "Show Comparison Plot." This allows the user to review the results and determine how to improve the return period of the bridge when necessary. The plot shows each vessel-pier combination and the percentage contribution to the total annual frequency of collapse that resulted from that vessel-pier combination. The user can also separate the calculations so as to compare each pier and each vessel.

7.3.3.4 Print Report

VIOB gives the user the ability to print a report detailing the results. To print a report, the user clicks the "Print Report…" button on the "Results Viewer" window. There are six different sections that VIOB prints out as part of the report. When the Print Report window, shown in Figure 7-28, first appears the checkboxes for all six sections are checked, but the user has the ability to remove any section from the report. The six report sections are the cover page, summary page, pier and channel information, vessel fleet description, results comparison, and detailed calculations. A sample report from a VIOB analysis is included in APPENDIX C of this thesis. The objective of the VIOB report is to produce a comprehensive outline of the analysis which can serve as both an informative report and a hard copy of all data used in the analysis. The VIOB report is designed to look elegant as if it were made on a computer but without sacrificing the details of a handwritten report.

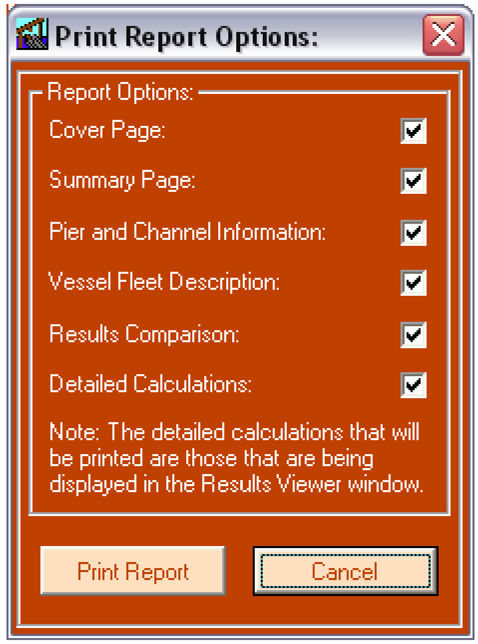


Figure 7-28: Print Report Screen Shot

The cover page is simply a front page to the report which details the name of the bridge, the TxDOT Structure ID, the waterway, the roadway, the engineer involved, and the date the report was created.

The summary page is a quick overview or abstract of what the geometry of the bridge looks like, some very basic data about the channel and the vessel fleet, and the basic results of the analysis.

Pier and channel information are also summarized in detail. All data about each pier are displayed in table format similarly, all data about the channel, is also displayed.

A set of tables with all of the vessel information is portrayed in the vessel fleet description section of the VIOB Report. A table with all of the vessel fleet components is always presented in this report section. Separate tables for barge groups, ships, tugs, and barges are presented. If a specific class of vessel is not in the vessel fleet, a table is not included in the report for that vessel class. The tug and barge tables will list all tugs and barges in the vessel fleet as well as all tugs and barges involved in any barge groups that are in the vessel fleet.

The results comparison section of the VIOB Report is a set of three figures. The first figure shows a comparison of every vessel-pier combination and how much it influences the results. The second figure is a comparison of the contribution to bridge collapse due to each of the vessels. A comparison of all of the piers is the third figure in the results comparison section.

The final section of the VIOB Report includes the detailed calculations. For every vessel-pier combination, VIOB will produce a detailed listing of all of the calculations and expressions used to get each result. The report looks similar to the "Results Viewer" display. All of the plots that are drawn for the results viewer are also drawn in the detailed calculation section. The first page of the detailed calculation section is a summary of all of the annual frequency of collapse estimates for every set of vessel-pier combinations.

The user should be cautious when printing reports as the number or runs printed will be very large if there are many vessels and piers. The detailed calculation section prints six pages for every unique vessel-pier combination. Therefore, the size of this report can grow rapidly. If the user selects a specific vessel and pier before clicking the "Print Report" button on the "Results Viewer" window, only that detailed calculation will be printed. This can be a better approach to printing the report.

7.4 VIOB CONCLUSION

7.4.1 Advantages of VIOB

Performing a vessel impact analysis on a bridge can be very time-consuming and tedious. VIOB turns a difficult problem into a very easy manageable problem. VIOB is a more useful software program for performing vessel impact analysis than any previous automated attempts.

7.4.2 Future Features

While VIOB has many remarkable features, there is much room for enhancements and improvements. Future features may include integrating structural analysis software directly into VIOB, creating a 3D channel profile from the database, 3D viewing of the bridge, more accurate probability of collapse calculations, improved graphics, and real-time database updating. As this is only the first version of VIOB, certain kinks are bound to be present. With rigorous testing of VIOB, future versions will be much more reliable and will likely be even more user-friendly.

CHAPTER 8
Conclusions

8.1 SUMMARY OF RESEARCH

The collapse of the Queen Isabella Causeway in 2001 due to a vessel collision was an alarming message to the state of Texas that vessel impact on bridges is a serious issue and ma need to be a consideration for all bridges spanning waterways. The failure of the Queen Isabella Causeway resulted in the stranding of thousands of people on South Padre Island, economic losses, and most disturbingly, several fatalities. The Texas Department of Transportation funded a research project at The University of Texas that was aimed at evaluating the AASHTO LRFD code specifications for vessel impact on bridges.

The goals of the present study were to help develop a database on bridges, waterways, and vessel traffic for Texas, and to make use of this database in computations of the annual frequency of bridge collapses due to vessel impact. A stand-alone computer program, VIOB, was developed to meet the objectives of this research. The program incorporates a database and performs analysis using Method II of the AASHTO LRFD code Specifications. It also introduces the possibility of an alternative method for computing the probability of collapse.

Past research related to vessel impact on bridges is sparse. Such research did not begin in the United States until the Sunshine Skyway Bridge in Tampa Bay, Florida collapsed in 1980 when a ship collided with one of the bridge's main piers. Today, numerous states such as Florida, Louisiana, and Texas to name a few are actively involved in efforts for safety of bridges against vessel impacts.

Currently the 2004 AASHTO LRFD design code is used to evaluate bridges against vessel impact. Bridges are required to meet a specified maximum allowable annual frequency of collapse which is computed using a probabilistic analysis. A "regular" bridge must have a return period associated with collapse due to impact of at least 1000 years. The total annual frequency of collapse of a bridge is the sum of the annual frequencies of collapse considering each pier in the bridge and each vessel passing it.

The annual frequency of collapse is evaluated as the product of the number of vessels passing a bridge per year, the probability of aberrancy, the geometric probability, and the probability of collapse. Probability of aberrancy is the probability that a vessel will stray off its intended course. If a vessel becomes aberrant, the probability that it will strike the bridge is defined as the geometric probability. The probability of collapse is defined as the probability that the bridge will collapse given that it is struck by an aberrant vessel. An assumption is usually made that the collapse of the pier in question leads to bridge collapse.

While the underlying basis for probability of aberrancy and geometric probability calculations is well justified, little research has been performed on barge-to-pier collisions to support the AASHTO LRFD code method for evaluating probability of collapse. The code has, due to lack of data on barge-pier collisions, relied on older ship-ship collision studies, for example. In the present study, an alternative approach based on modeling is proposed in order to obtain the probability of collapse.

The alternative approach that can be implemented into the software program requires finite element studies to obtain vessel impact forces and nonlinear static pushover analysis to obtain pier ultimate strengths. Consideration for the variability in material properties, vessel loading condition, angle of impact, and height of impact is included in the procedure.

A user-friendly standalone computer program, named VIOB, has been developed. Using a comprehensive database that includes information on waterways, vessels, and traffic, VIOB can perform an entire bridge analysis for vessel impacts.

Given information related to the bridge and pier geometry, the waterway, and the vessel traffic at a given mile marker of a waterway, VIOB is able to produce an in-depth report detailing the calculations performed. The VIOB report not only provides information about the analysis performed, but also arranges the data so that the user can determine which vessels and piers most influence the vulnerability of the bridge. This allows the user to make educated decisions about ways to improve bridges that might not meet the AASHTO LRFD acceptance criteria.

8.2 RECOMMENDATIONS FOR FUTURE RESEARCH

There are many areas where further research can be carried out to attempt to improve the AASHTO LRFD vessel collision design procedure. The approach for calculating probability of collapse is an extremely difficult one to support because very few actual tests have been performed involving barge-to-pier collisions. While the computer models generated in this study overall research can simulate barge-to-pier collisions, it is impossible to know if the results are accurate without a real test to use as a reference. The few tests that have been done that involved barge-to-pier collisions are not very useful because the tests were performed at very slow velocities and may not simulate actual vessel impact scenarios. Further development of analytical models to determine vessel impact loads and ultimate strength of bridges is also necessary and can be validated with full-scale test results.

VIOB is a very robust program but there are still many improvements that can be made to it. Future versions of VIOB should include a more detailed library, enhanced features, and a better user interface. New features could include

3D plotting of the bridge, built-in structural analysis capabilities, and a library with real-time updating especially on traffic trends.

APPENDIX A

Description of VIOB Database Tables

A.1 ALTERNATIVE METHOD FOR ASSEMBLING DATABASE

For most data being input into the program, it is easy to use the VIOB database libraries to enter the data and then choose which vessels are to be used. However, if one is entering a large amount of data, it can sometimes be easier to create the database in Microsoft Access outside of VIOB, and simply have VIOB read in the database. This appendix describes how each of the vessel-related tables needs to be created in the VIOB database.

For each of the tables below, the names used must be entered exactly as shown. If the tables and table headers are not properly formatted and named, VIOB will not be able to understand them. For each table, a description of the table, the database table name, the index for the table, and a list of the column headers is given.

To study some examples of how the tables should look one can open the existing VIOB database in Microsoft Access and review the format in which the tables are assembled. Besides the seven tables listed below, there will be others in the VIOB database. Those tables are used for various parts of the program; the user should be very cautious about modifying those tables. If the tables are incorrectly changed, VIOB will no longer understand them and will not function properly.

A.1.1 Waterways

A.1.1.1 Description

This table is a list of waterway names, the mile markers associated with each waterway, and the channel information associated with those mile markers.

A.1.1.2 Database Table Name

The database table name is "WaterwayInfo"

A.1.1.3 Index

The "WaterwayInfo" table should be indexed by "Name" and then "Milemarker"

A.1.1.4 Column Headers

Table A-1: Column headers for "WaterwayInfo" database table

Column Header	Units	Data Type	Description
Name	-	text	The name of the waterway. i.e. Gulf Intercoastals Waterway (GIWW)
Milemarker	-	number	A given mile marker on a waterway
VesselFleet	-	text	The name of the vessel fleet that passes that mile marker
ParCurrent	knots	number	The current velocity parallel to the direction of vessel traffic
PerpCurrent	knots	number	The current velocity perpendicular to the direction of vessel traffic
TrafficDensity	-	text	The traffic density at any given mile marker. Entered as High, Average, or Low. See AAHSHTO G.S. 4.8.3.2
MinimumImpactSpeed	ft / s	number	See AASHTO LRFD 3.14.6

A.1.2 Vessel Fleets

A.1.2.1 Description

This table contains a list of all vessel fleets, the vessels associated with each vessel fleet, and the properties associated with each vessel as they relate to the vessel fleet.

A.1.2.2 Database Table Name

The database table name is "VesselFleets"

A.1.2.3 Index

The "VesselFleet" table should be indexed by "Name" then "VesselClass" then "VesselType" then "VesselSize" and then "LoadorUnload"

A.1.2.4 Column Headers

Table A-2: Column headers for "VesselFleet" database table

Column Header	Units	Data Type	Description
Name	-	text	The name of the vessel fleet
VesselClass	-	text	The Class of vessel. Four options: Barge, Tug, Ship, Barge Group
VesselType	-	text	The Type of vessel If VesselClass = Barge Group, use BargeGroupName for VesselType
VesselSize	-	text	The Size of vessel If VesselClass = Ship, VesselSize = DWT If VesselClass = Tug, VesselSize = Horsepower If VesselClass = Barge, VesselSize = Barge Size If VesselClass = Barge Group, VesselSize = N/A
NumTrips	Trips/Yr	number	The numer of trips a given vessel makes per year past the bridge
LoadorUnload	-	True/False	Whether the vessel is loaded or unloaded. True if Loaded, False if Unloaded
VesselSpeed	knots	number	The velocity of the vessel

A.1.3 Barge Group Description

A.1.3.1 Description

This table describes the tug type and size and the number of barges in the barge group.

A.1.3.2 Database Table Name

The database table name is "BargeGroupDescrip"

A.1.3.3 Index

The "BargeGroupDescrip" table should be indexed by "Name"

A.1.3.4 Column Headers

Table A-3: Column headers for "BargeGroupDescrip" database table

Column Header	Units	Data Type	Description
Name	-	text	The name of the barge group
TugType	-	text	The type of tug in the barge group
TugSize	-	text	The horsepower of tug in the barge group
Width	barges	number	The number of barges wide the barge group is. In the y or j direction
Length	barges	number	The number of barges long the barge group is. In the x or i direction

A.1.4 Barge Group Arrangement

A.1.4.1 Description

This table describes the type and size of each barge and where it is located spatially in the barge group.

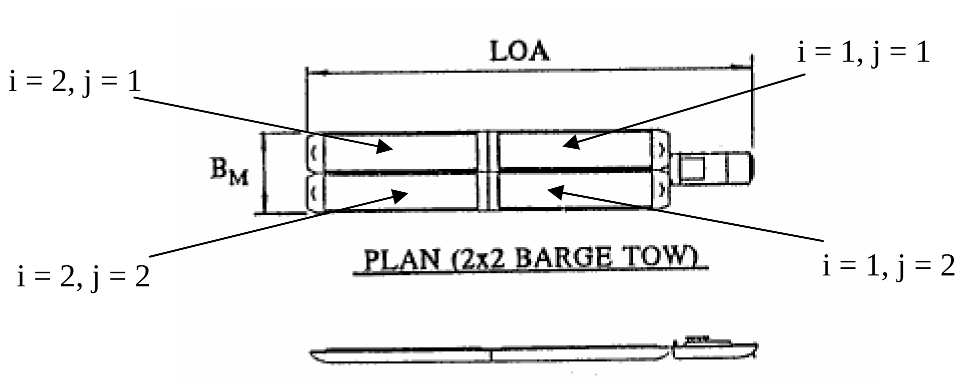


Figure A-1: Designation of i and j in a barge group

A.1.4.2 Database Table Name

The database table name is "BargeGroupArrange"

A.1.4.3 Index

The “BargeGroupArrange” table should be indexed by “Name” then by “i” and then by “j”

A.1.4.4 Column Headers

Table A-4: Column headers for “BargeGroupArrange” database table

Column Header	Units	Data Type	Description
Name	-	text	The name of the barge group
BargeType	-	text	The type of barge that is in this i,j position
BargeSize	-	text	The size of barge that is in this i,j position
i	-	number	The x position of a barge in a barge group
j	-	number	The y position of a barge in a barge group

A.1.5 Barges

A.1.5.1 Description

This table consists of all of the different types of barges that are in any waterway and the dimensions of those barges.

A.1.5.2 Database Table Name

The database table name is “Barges”

A.1.5.3 Index

The “Barges” table should be indexed by “Type” and then by “Size”

A.1.5.4 Column Headers

Table A-5: Column headers for "Barges" database table

Column Header	Units	Data Type	Description
Type	-	text	The type of barge. e.g. "Covered Hopper"
Size	-	text	The size of the barge. e.g. "Jumbo"
Length	ft	number	See AASHTO G.S. Figure 3.5.1-1
Width	ft	number	See AASHTO G.S. Figure 3.5.1-1
EmptyDraft	ft	number	See AASHTO G.S. Figure 3.5.1-1
LoadedDraft	ft	number	See AASHTO G.S. Figure 3.5.1-1
EmptyDisplacement	ton	number	See AASHTO G.S. Figure 3.5.1-1
LoadedDisplacement	ton	number	See AASHTO G.S. Figure 3.5.1-1

A.1.6 Tugs

A.1.6.1 Description

This table consists of all of the different types of tugs that are in any waterway and the dimensions of those tugs.

A.1.6.2 Database Table Name

The database table name is "TugBoats"

A.1.6.3 Index

The "TugBoats" table should be indexed by "Type" and then by "Horsepower"

A.1.6.4 Column Headers

Table A-6: Column headers for "TugBoats" database table

Column Header	Units	Data Type	Description
Type	-	text	The type of tug. e.g. "Line Haul"
Horsepower	-	number	The horsepower of the tug. e.g. "2000"
Length	ft	number	See AASHTO G.S. 3.5 Table 3.5.1-2
Width	ft	number	See AASHTO G.S. 3.5 Table 3.5.1-2
Draft	ft	number	See AASHTO G.S. 3.5 Table 3.5.1-2
Displacement	ton	number	See AASHTO G.S. 3.5 Table 3.5.1-2

A.1.7 Ships

A.1.7.1 Description

This table consists of all of the different types of ships that are in any waterway and the dimensions of those ships.

A.1.7.2 Database Table Name

The database table name is "Ships"

A.1.7.3 Index

The "Ships" table should be indexed by "Type" and then by "DWT"

A.1.7.4 Column Headers

Table A-7: Column headers for "Ships" database table

Column Header	Units	Data Type	Description
Type	-	text	The type of ship. e.g. "Bulk Carrier"
DWT	tonne	number	The DWT of the ship e.g. "1000"
Length	ft	number	See AASHTO G.S. Figure 3.5.2-4
Beam	ft	number	See AASHTO G.S. Figure 3.5.2-4
BallDraftB	ft	number	See AASHTO G.S. Figure 3.5.2-4
BallDraftS	ft	number	See AASHTO G.S. Figure 3.5.2-4
LoadedDraft	ft	number	See AASHTO G.S. Figure 3.5.2-4
BallDisplacement	tonne	number	See AASHTO G.S. Figure 3.5.2-4
LoadedDisplacement	tonne	number	See AASHTO G.S. Figure 3.5.2-4

APPENDIX B

Analysis Example using VIOB

B.1 INTRODUCTION

A step-by-step example is presented to give the user some instructions for entering a new bridge, assigning bridge properties to the new bridge, and performing an analysis on the newly entered bridge. This example will not show how to use all of the features of VIOB nor how to enter information into the vessel library. For an extensive look at all of the features of VIOB, refer to Chapter 7.

B.2 EXAMPLE BRIDGE DESCRIPTION

In order to determine the return period for a bridge collapse due to vessel impact using VIOB, some basic information must be known by the user. The bridge data, pier geometry, and channel data must be known. For this example, the information has been summarized in Table B-1, Table B-2, and Table B-3.

Table B-1: Bridge Data

Bridge Name:	Colorado River - FM 521
TxDOT Structure ID:	131580084603009
Waterway:	Colorado River
Mile Marker:	100
Roadway:	FM 521
Importance Classification:	Regular

Table B-2: Pier Geometry

Pier	x Distance [1]	Pier Height	Pier Bottom Elevation [2]	Channel Bottom Elevation [2]	Diameter at HWL	H
	(ft)	(ft)	(ft)	(ft)	(ft)	(kips)
1	0	45	0	6.16	4	450
2	125	45	0.16	4.16	4	330
3	215	35	10.16	10.16	4	200
4	255	33	12.16	15.16	2	200

[1] Measured from Pier 1
[2] Measured from Bottom of Pier 1

Table B-3: Channel Data

Parallel Current Velocity:	1.185	knots
Perpendicular Current Velocity:	0.592	knots
Minimum Impact Speed:	1.689	ft/s
HWL Elevation [2] :	28.86	ft
NWL Elevation [2] :	9.16	ft
Navigable Channel Width:	100	ft
Navigable Channel CL [1] :	62.5	ft
Channel Region Type:	Transition	
Channel Turn Angle:	34	deg
Traffic Density:	Low	

[1] Measured from Pier 1
[2] Measured from Bottom of Pier 1

B.3 CREATE NEW BRIDGE

The first step in creating a new bridge is to select the “New Bridge” option from the “Start Menu.” Once the “New Bridge” option is selected, the user should click the “Start VIOB” button to bring up the “New Bridge” window. See Figure B-1.

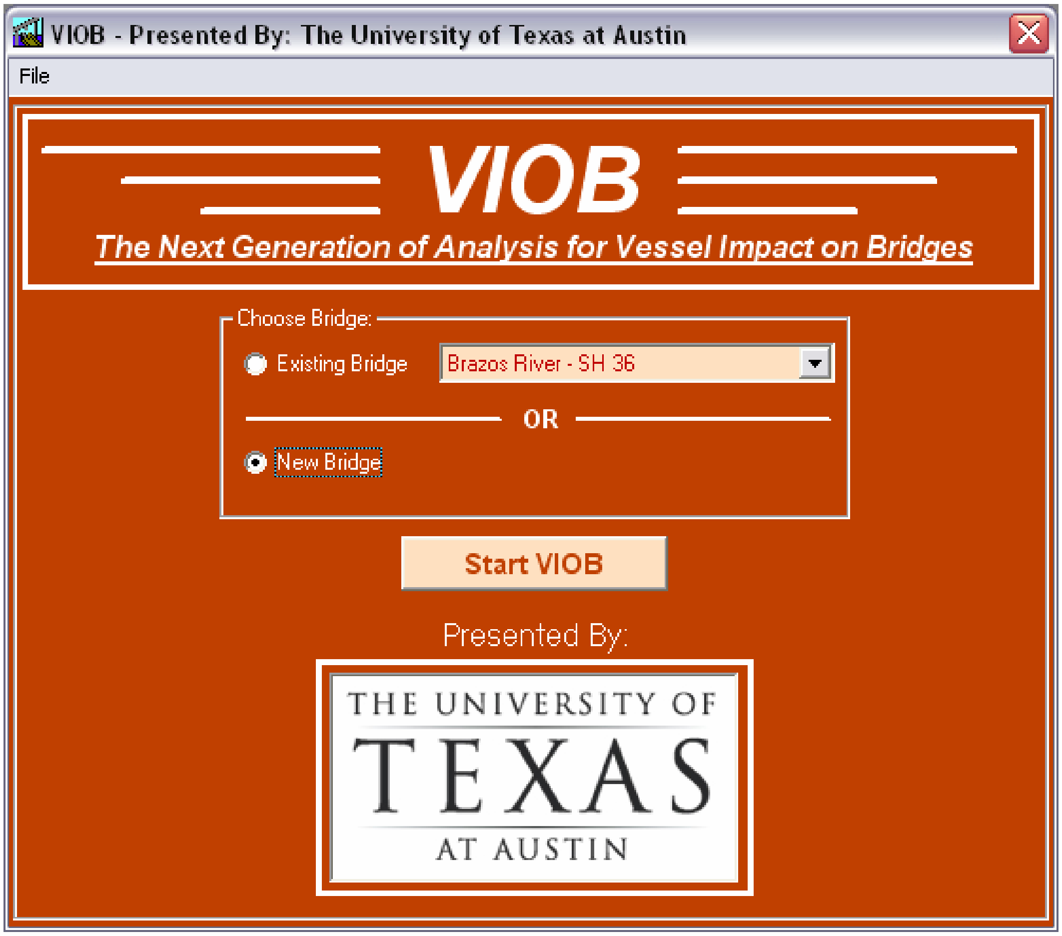


Figure B-1: "New Bridge" option selected from the "Start Menu"

When the "New Bridge" window pops up, the user should then enter the bridge information. The user must enter the cross waterway, the roadway, the TxDOT Structure ID, the number of piers, and the unit system that the user intends to use. See Figure B-2.

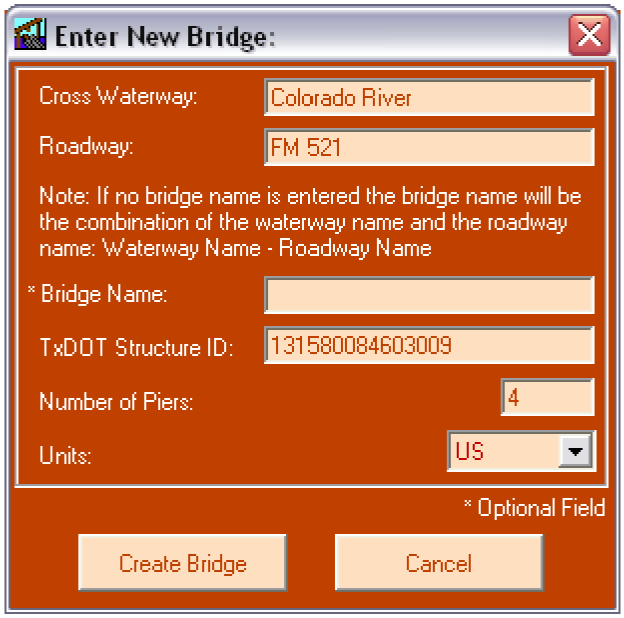


Figure B-2: Bridge information entered into the "New Bridge" window

Once the user has entered all of the information into the "New Bridge" window, the "Create Bridge" button is pressed. The "New Bridge" window will hide itself and the user will be taken to the "Main Page." The initial display is a standardized bridge showing the number of piers that the user entered. In this case four piers each with a default height of 50 feet and spaced 100 feet from each other will be shown. The default centerline of the navigable channel is the midpoint of the center span of the bridge. See Figure B-3.

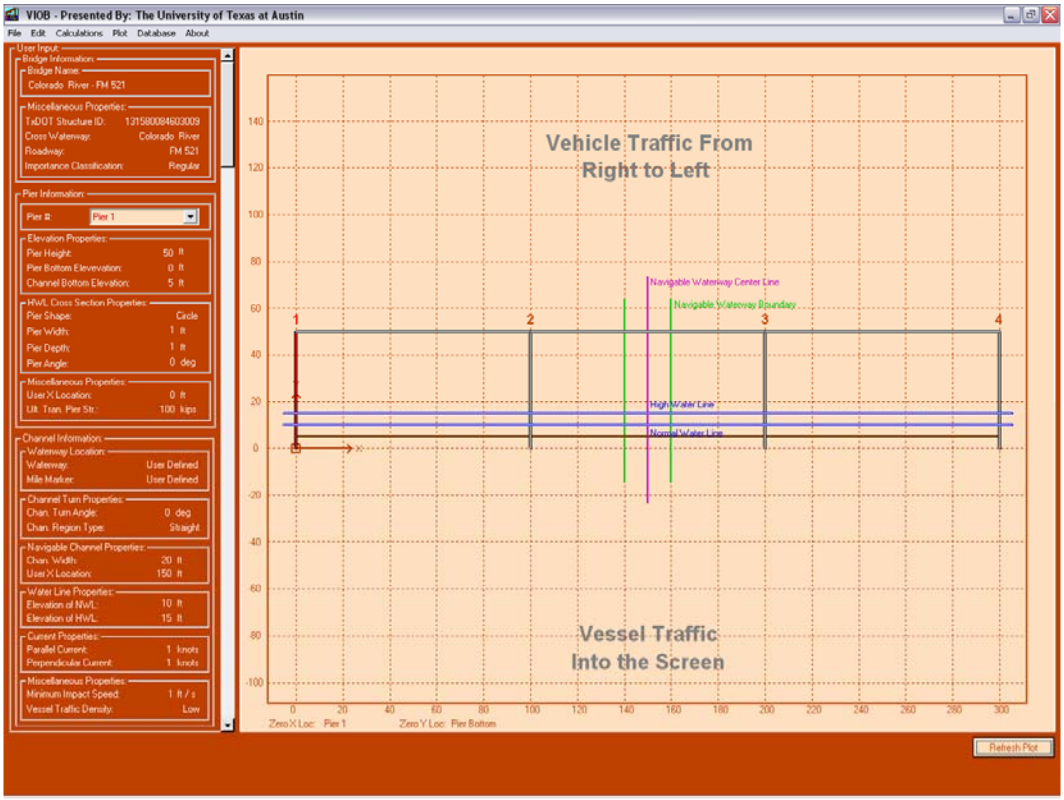


Figure B-3: The "Main Page" showing the newly created bridge

B.4 EDIT BRIDGE INFORMATION

With the new bridge created, one can now edit the bridge information. To do this, the user clicks on **Edit > Bridge Data…** to open the "Edit Bridge" window. In the "Edit Bridge" window, the user needs to select the bridge's importance classification. The default value is "Regular." Once the importance classification is selected, the user clicks the "OK" button to return to the "Main Page." See Figure B-4 and Figure B-5.

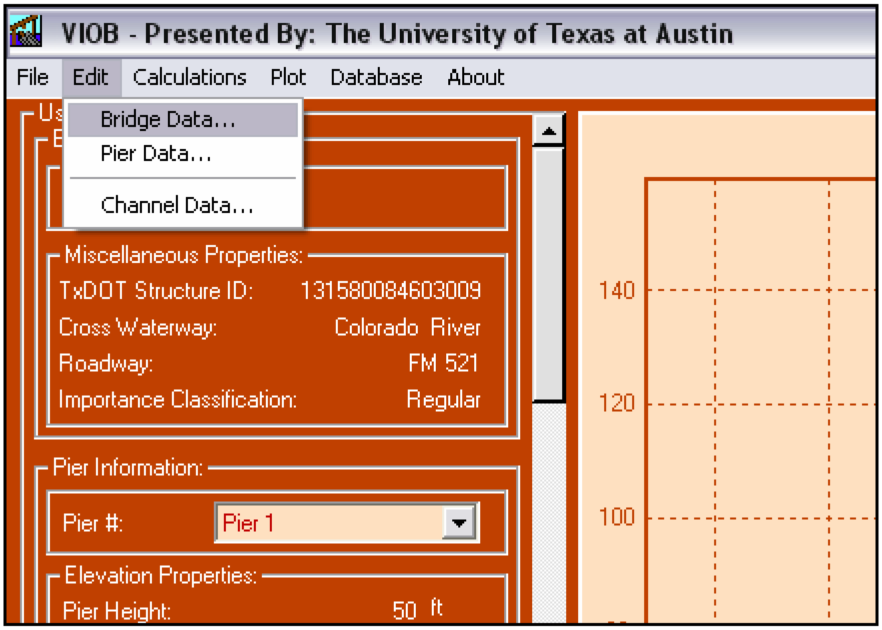


Figure B-4: Selecting Bridge Data… from the "Edit" menu

Figure B-5: "Edit Bridge" window with importance classification entered

B.5 EDIT PIER GEOMETRY

With the bridge data entered properly, the user can now edit the pier geometry. To edit the pier geometry, the user first selects the pier that he/she wants to edit in the pier pull-down menu on the "Main Page" and then clicks on **Edit > Pier Data…** which will bring up the "Edit Pier" window. The user must do this for each of the four piers. See Figure B-6 to Figure B-10. After the information for each pier is entered, the user clicks the "OK" button to return to the "Main Page."

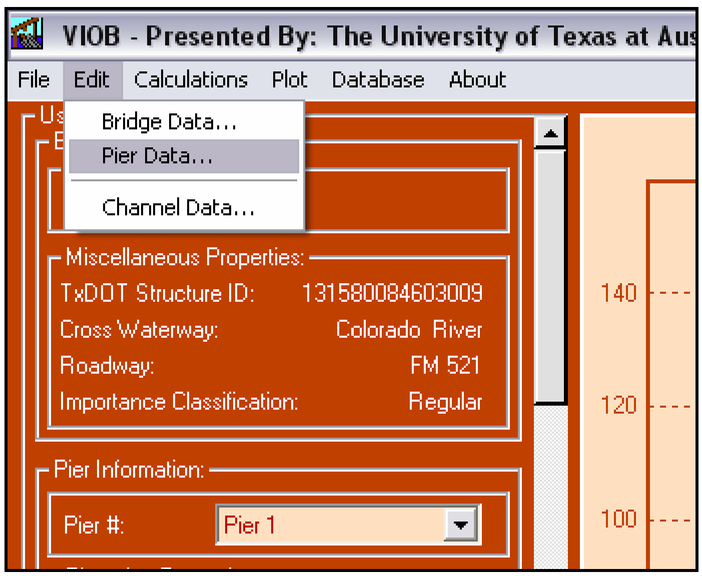


Figure B-6: Selecting Pier Data… from the "Edit" menu

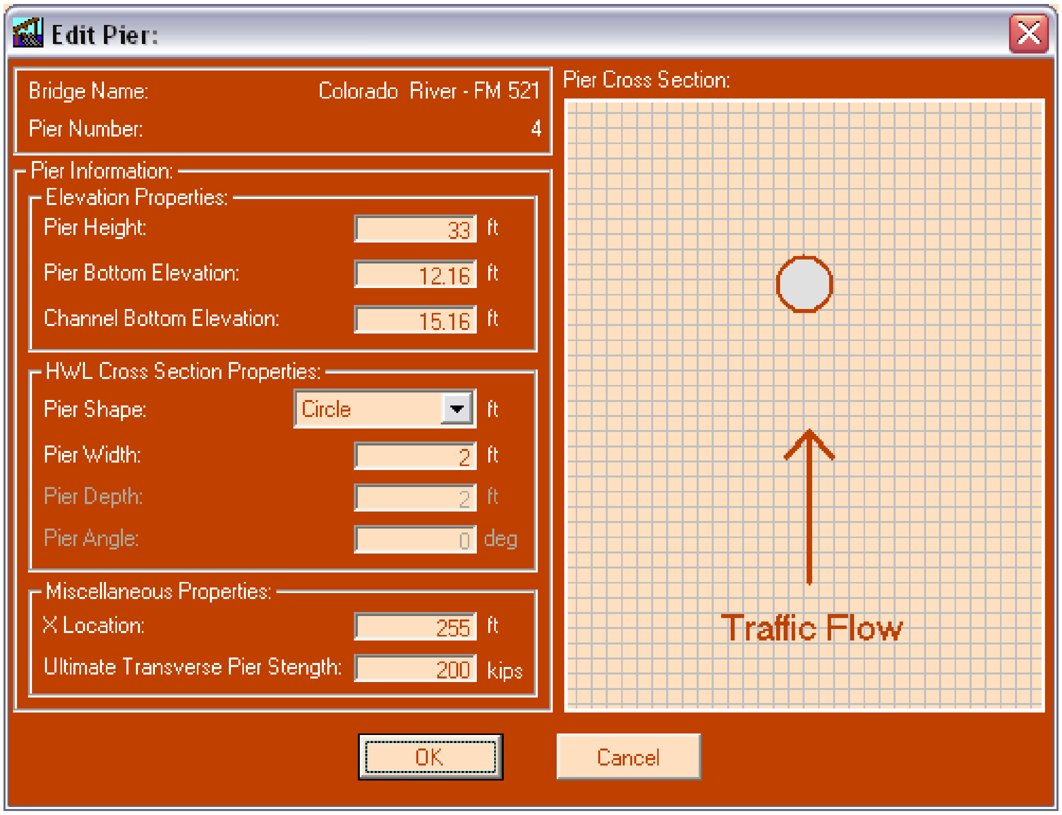


Figure B-7: Pier 4 being edited in the "Edit Pier" window

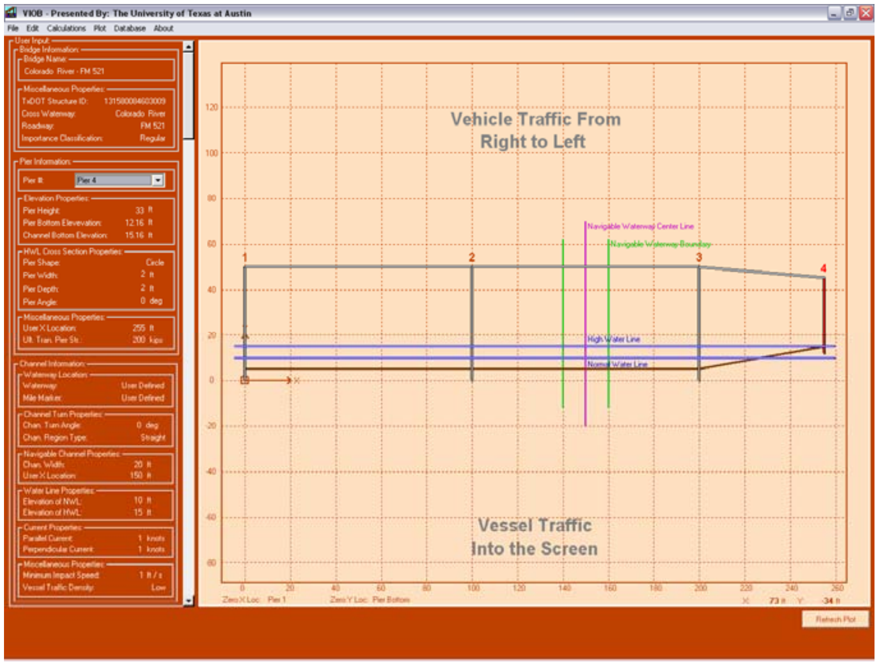


Figure B-8: "Main Page" after Pier 4 has been edited

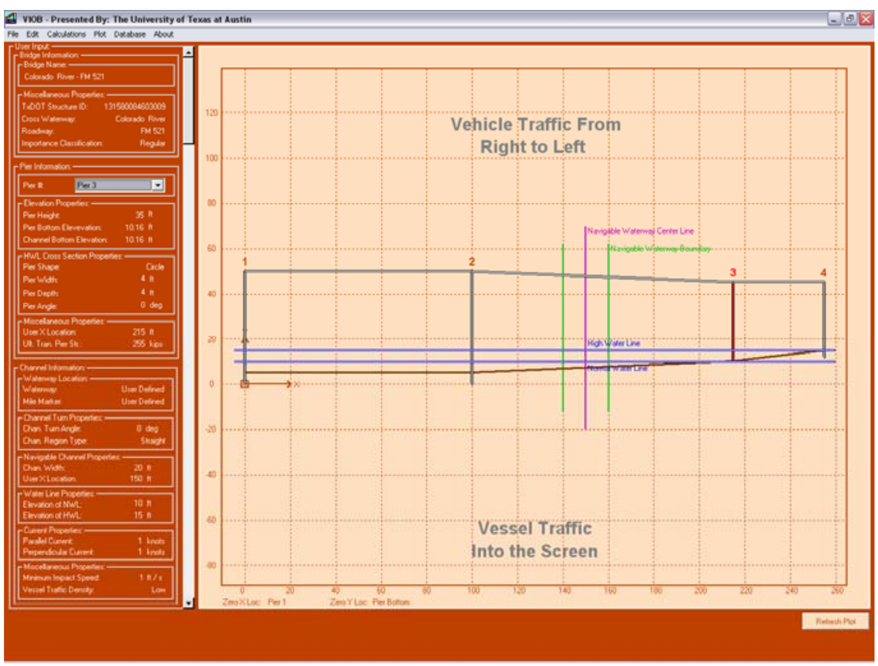


Figure B-9: "Main Page" after Pier 3 has been edited

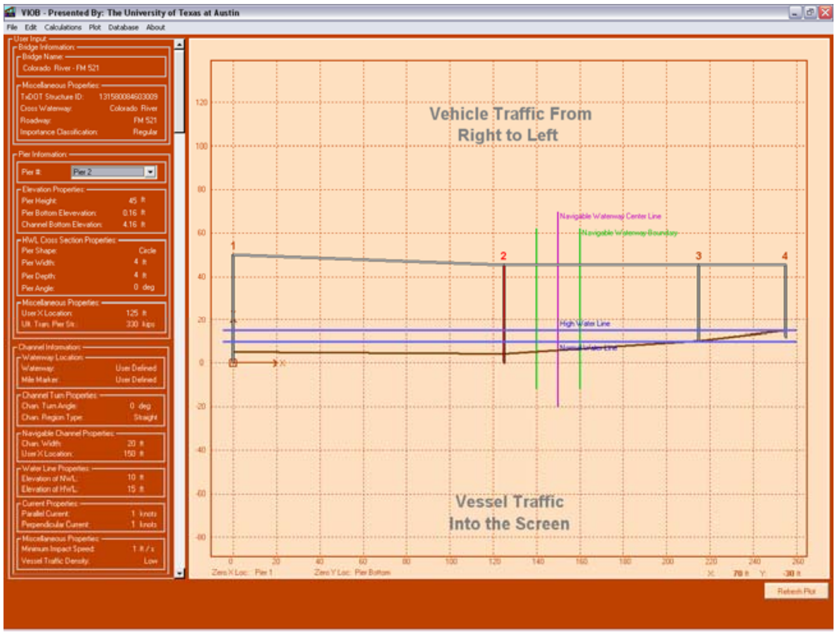


Figure B-10: "Main Page" after Pier 2 has been edited

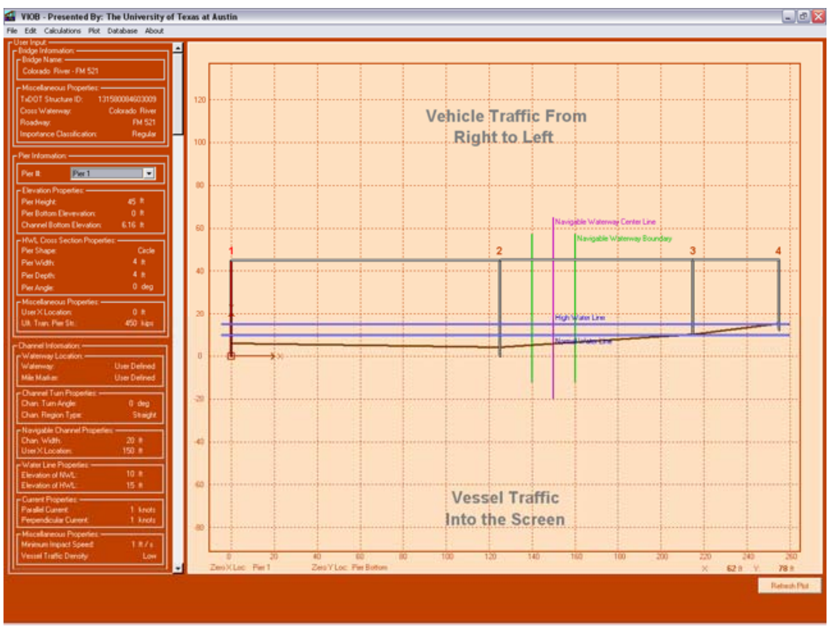


Figure B-11: "Main Page" after Pier 1 has been edited

B.6 EDIT CHANNEL DATA

After the pier geometry has been entered, the next step is to edit the channel data. To do this the user clicks on **Edit > Channel Data…** to open the "Edit Channel" window. See Figure B-12 and Figure B-13.

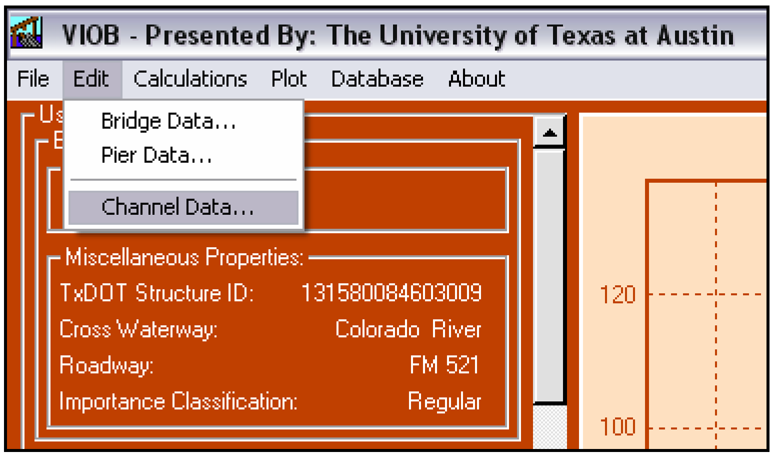


Figure B-12: Selecting channel data from the "Edit" menu

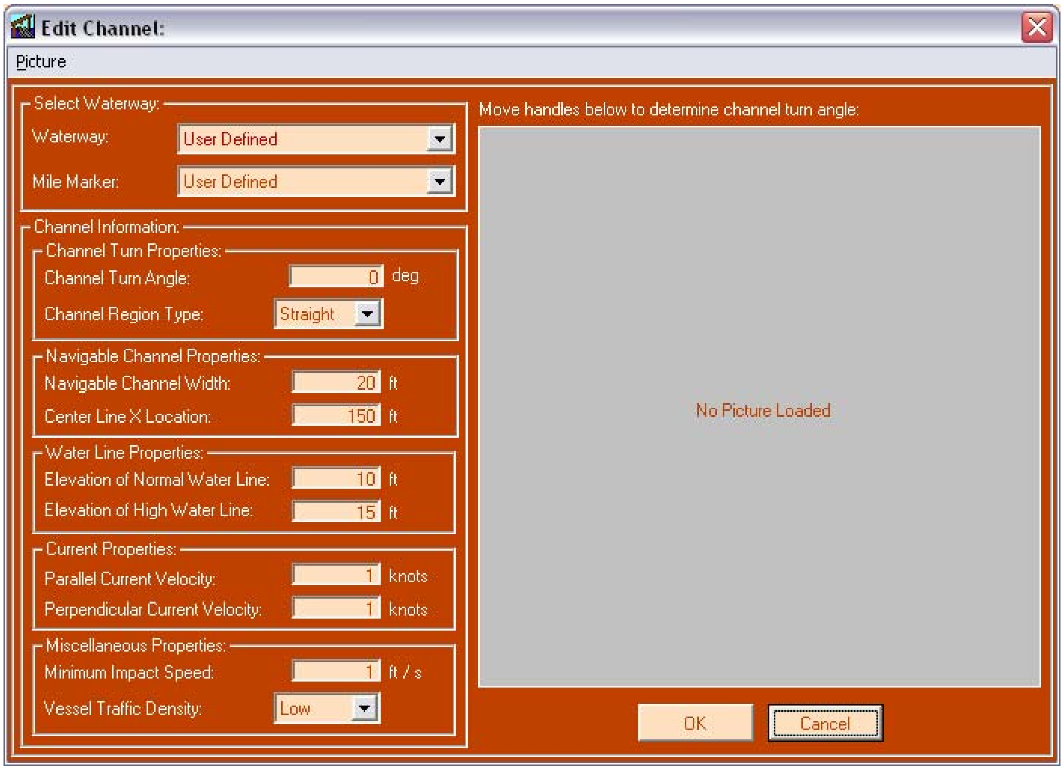


Figure B-13: Default "Edit Channel" window

When the user opens the "Edit Channel" window for the first time on a bridge, the aerial photo of that bridge will not be loaded. To do this, the user can click **Picture** > **Load…** which will bring up the file browse window to allow the user to select any available bitmap image of the aerial photo for this bridge. See Figure B-14. Once the aerial photo of the bridge has been loaded, the channel window will include the built-in protractor for determining the channel angle. The user can now enter all of the channel information. See Figure B-15.

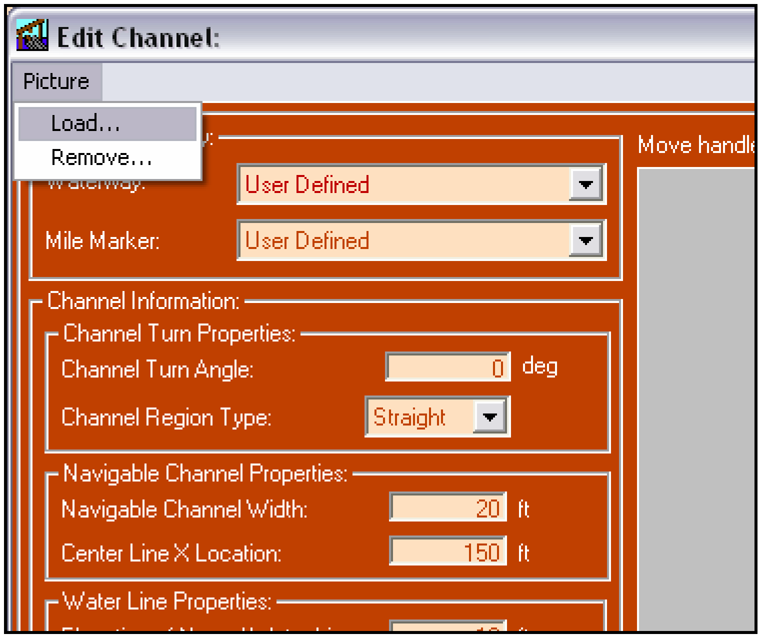


Figure B-14: Selecting the load option from the "Picture" menu

In this example, the waterway and mile marker already exist in the VIOB library; therefore, the user can select the waterway and mile marker from the pull-down menu in the "Edit Channel" window. Selecting the waterway and the mile marker will automatically fill in the current velocities, minimum impact speed, and traffic density. To edit the channel turn angle, the user moves the square handle to adjust the protractor's origin and then moves the circular handles to determine the angle of the channel. If no aerial photo exists, the user can enter the angle manually instead. Once all of the channel data is entered, the user clicks the "OK" button to return to the "Main Page."

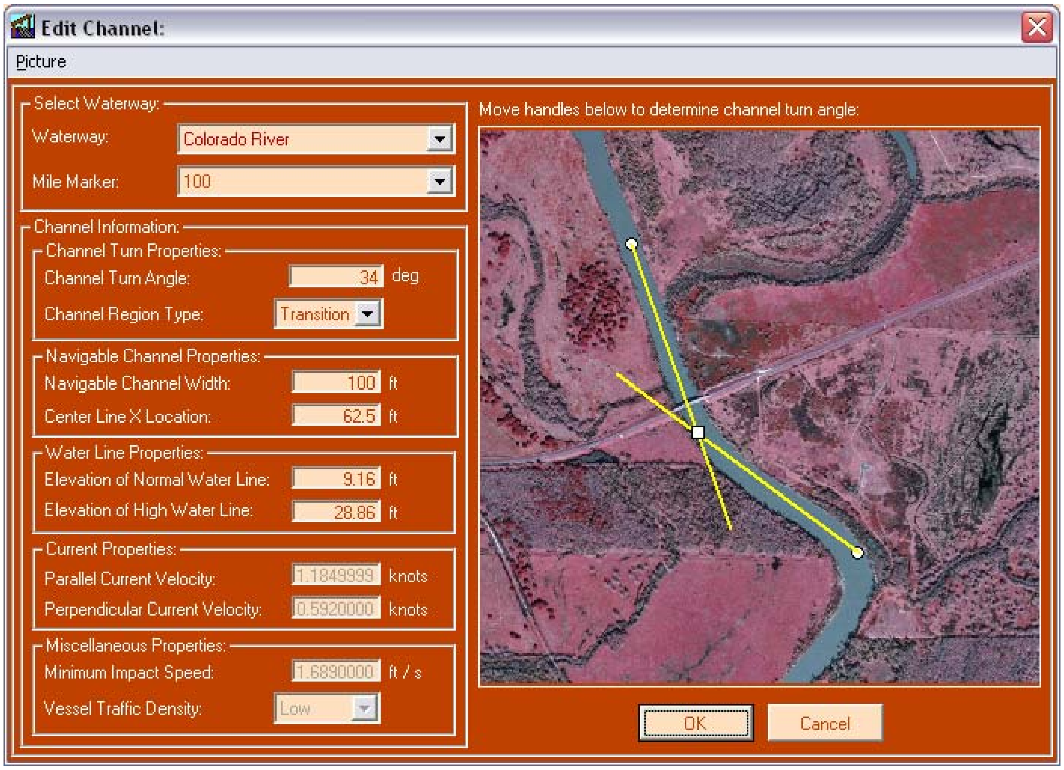


Figure B-15: "Edit Channel" window with information entered and aerial picture loaded

At this point, all of the necessary information is available and the "Main Page" is displayed. See Figure B-16.

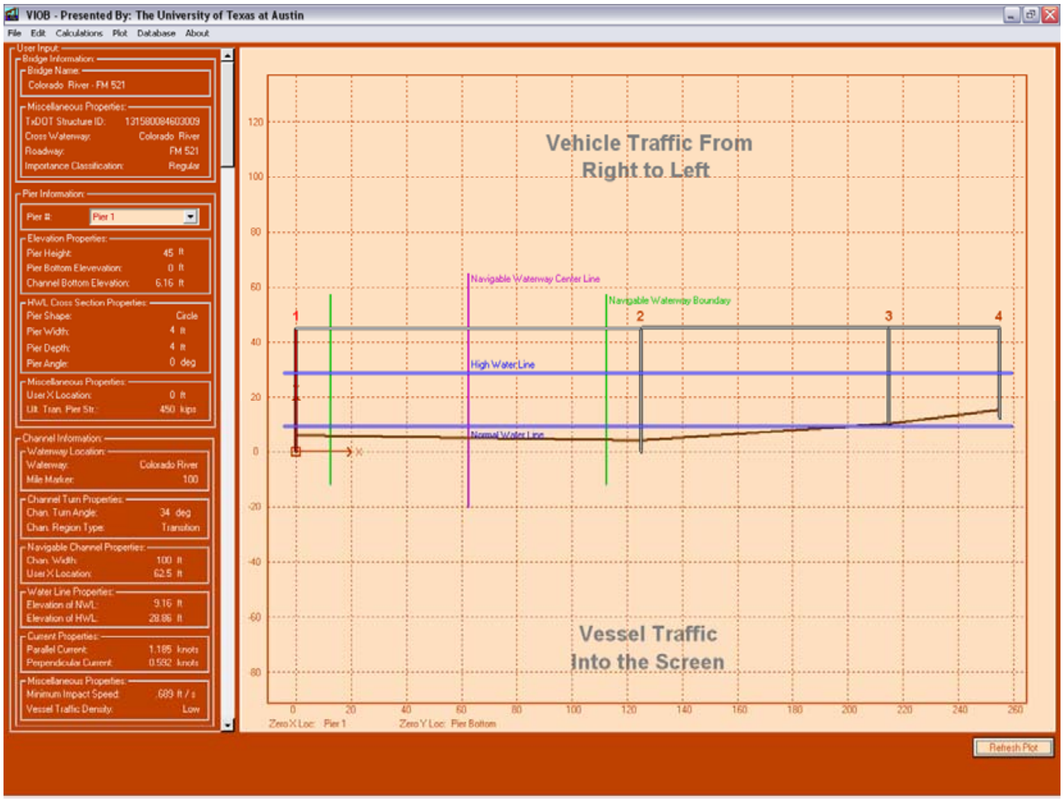


Figure B-16: The "Main Page" after the channel data has been edited

B.7 RUN ANALYSIS

With all of the information about the bridge entered into VIOB, the analysis can now be run. To run an analysis, the user clicks on **Calculations > Run…** on the "Main Page" which will open the "Analysis Wizard." See Figure B-17 and Figure B-18. In the "Analysis Wizard" the user must enter his/her name only as all of the other information will have been automatically filled out for the user. VIOB knows the vessel fleet because the vessel fleet is assigned to the waterway and mile marker assigned to the bridge previously.

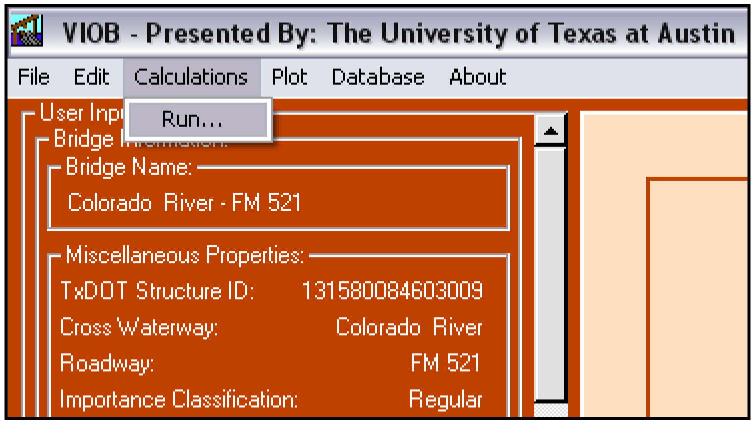


Figure B-17: Selecting the run option from the "Calculations" menu

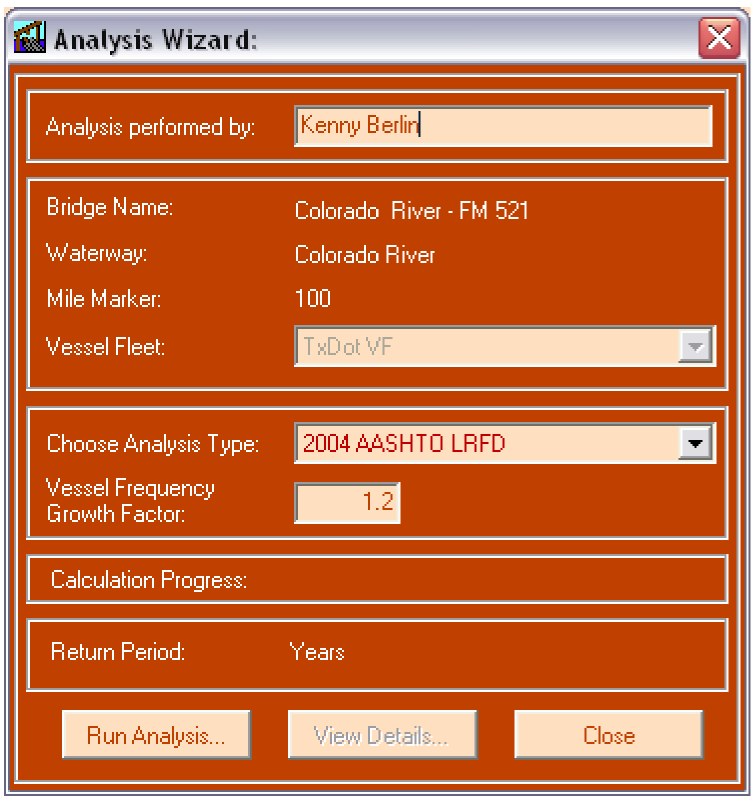


Figure B-18: "Analysis Wizard" before the analysis is run

The user must next click the "Run Analysis…" button on the "Analysis Wizard" window. VIOB will then determine the return period of the bridge and summarize the results on the same window. The user can track the progress of the calculations by looking at the calculation progress bar.

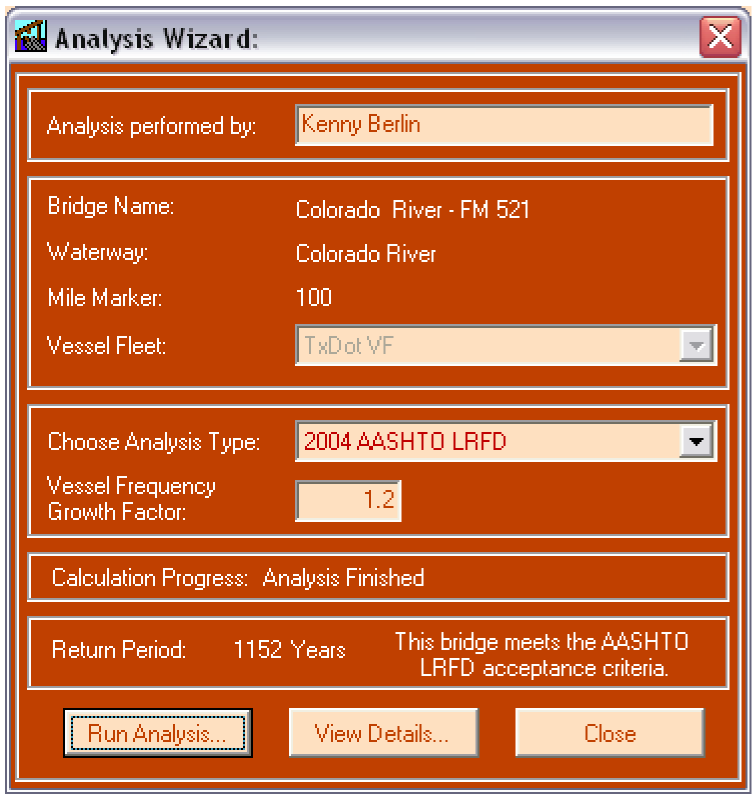


Figure B-19: "Analysis Wizard" window after "Run Analysis…" has been clicked

Once the analysis has been run, the user can view a detailed set of results by clicking on the "View Details" button. For more information about detailed results, refer to Chapter 7.

APPENDIX C
Sample VIOB Report

C.1 DESCRIPTION

This appendix contains a sample VIOB Report for a single bridge analysis. For this example, all six sections of the report were printed. To limit the number of pages here, the report has been reproduced to show two report pages on every one page that follows.

VIOB REPORT

Bridge Name: San Jacinto River - EB IH-10
TxDOT Structure ID: 121020050801317
Waterway: User Defined
Roadway: EB IH-10

Report Created By: Kenny Berlin

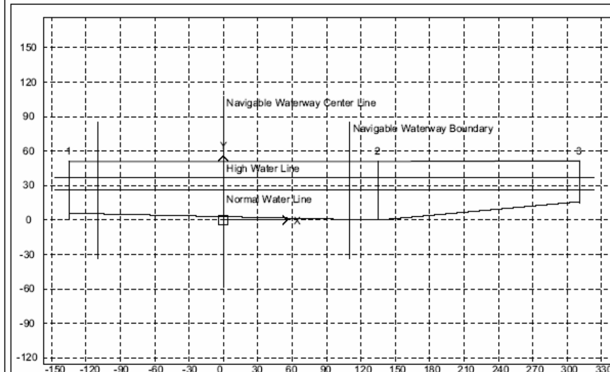
May 3, 2005

VIOB **Presented By: The University of Texas at Austin**
The Next Generation of Analysis for Vessel Impact on Bridges

VIOB **Presented By: The University of Texas at Austin**
The Next Generation of Analysis for Vessel Impact on Bridges

Results Summary:

Bridge Name:	San Jacinto River - EB IH-10	**TxDOT Structure ID:**	121020050801317
Waterway:	User Defined	**Vessel Fleet:**	SJR VF
Roadway:	EB IH-10	**Milemarker:**	User Defined
Analysis Performed By:	Kenny Berlin	**Analysis Date:**	5/3/2005
Analysis Type:	2004 AASHTO LRFD	**Analysis Time:**	11:03:50 AM



Annual Frequency of Collapse:	2.887757E-03	1/Yr
Return Period:	346	Years
Importance Classification:	Regular	
Pass/Fail:	Fail	

This bridge does NOT meet the AASHTO LRFD acceptance criteria.

Page 1

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Pier and Channel Information:

Channel Information:

Waterway Name:	User Defined				
Mile Marker:	User Defined				
Normal Water Line:	26.5	ft	Channel Width:	220	ft
High Water Line:	36.7	ft	Channel Region Type:	Bend	
Parallel Current:	1.185	knots	Channel Turn Angle:	15	deg
Perpendicular Current:	0.593	knots	Traffic Density:	Low	
Minimum Impact Speed:	1.688	ft / s			

Table 1: Pier Information

Pier Number:		Pier 1	Pier 2	Pier 3
Pier Height:	ft	51	51	36.5
Pier Bottom Elevation:	ft	0	0	15
Channel Elevation:	ft	6	0	16
User X Location:	ft	-135	135	311
Ultimate Transverse Pier Strength:	kips	997	997	815
Pier X-Section Shape:		Circle	Circle	Circle
Pier X-Section Depth:	ft	4.75	4.75	3.75
Pier X-Section Width:	ft	4.75	4.75	3.75
Pier X-Section Angle:	deg	0	0	0

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The Next Generation of Analysis for Vessel Impact on Bridges

Vessel Fleet Description:

Table 2: Vessel Fleet Components

Vessel Name	Vessel Class	Vessel Type	Vessel Size	Vessel Frequency	Loaded or Unloaded	Vessel Velocity
				(Trips/Year)		(knots)
V1	Barge Group	TXDOT BG 4	N/A	677	Loaded	6
V2	Barge Group	TXDOT BG 4	N/A	677	Unloaded	6

Table 3: Barge Group Information

Vessel Name	Barge Group Type	Barge Group Size	Length	Width	Displacement	Draft
			(ft)	(ft)	(tonne)	(ft)
V1	TXDOT BG 4	N/A	257	35	1542.214	9
		V1-TG	V1-BG			
V2	TXDOT BG 4	N/A	257	35	567.7162	9
		V2-TG	V2-BG			

Table 4: Tug Information

Vessel Name	Tug Type	Tug Horsepower	Length	Width	Displacement	Draft
			(ft)	(ft)	(tonne)	(ft)
V1-TG	TXDOT Tug	1	62	20	181.4369	9
V2-TG	TXDOT Tug	1	62	20	181.4369	9

Table 5: Barge Information

Vessel Name	Barge Type	Barge Size	Length	Width	Displacement	Draft
			(ft)	(ft)	(tonne)	(ft)
V1-BG	Covered Hopper	TXDOT Jumbo	195	35	1360.777	7
V2-BG	Covered Hopper	TXDOT Jumbo	195	35	386.2792	2

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The Next Generation of Analysis for Vessel Impact on Bridges

Results Comparison:

Figure 1: Comparison of Particular Vessel Passing a Particular Pier

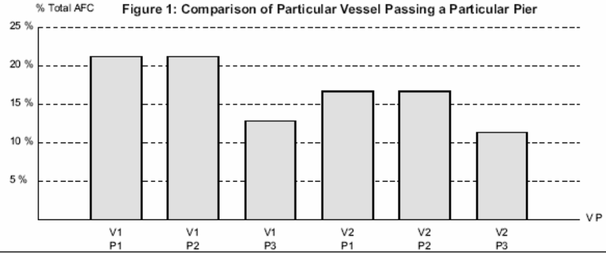


Figure 2: Comparison of Particular Vessel Passing All Piers

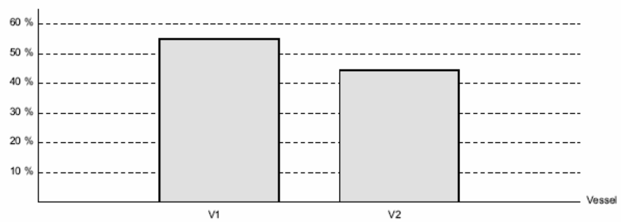
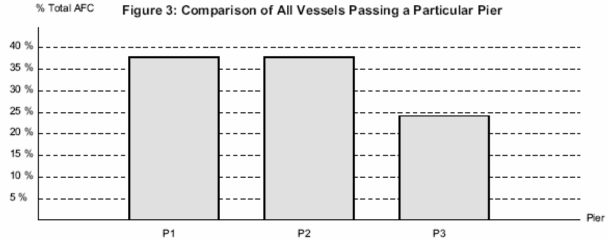


Figure 3: Comparison of All Vessels Passing a Particular Pier



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The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations:

Table 6: AFC Summary

(AASHTO LRFD 3.14.5-1)

$$AFC = (N)(PA)(PG)(PC)$$

Vessel i - Pier j	N	PA	PG	PC	AFC
Vessel 1 - Pier 1	812.4	0.000285	0.053714	0.049254	0.000613
Vessel 1 - Pier 2	812.4	0.000285	0.053714	0.049254	0.000613
Vessel 1 - Pier 3	812.4	0.000285	0.028937	0.055482	0.000372
Vessel 2 - Pier 1	812.4	0.000285	0.053714	0.038662	0.000481
Vessel 2 - Pier 2	812.4	0.000285	0.053714	0.038662	0.000481
Vessel 2 - Pier 3	812.4	0.000285	0.028937	0.049025	0.000329
				Total AFC:	0.002889

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The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Vessel 1 - Pier 1

Vessel Frequency Calculations (V1-P1):

Projected Vessel Frequency (N):	812.4	Trips/Yr
Current Vessel Frequency:	677	Trips/Yr
Growth Factor:	1.2	

Probability of Aberrancy Calculations (V1-P1):

Probability of Aberrancy (PA):	0.000285	1/Yrs

(AASHTO LRFD 3.14.5.2.3-1)

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

Aberrancy Base Rate (BR):	0.00012	
Correction Factor for Bridge Location (RB):	1.333	

(AASHTO LRFD 3.14.5.2.3-4)

$$R_B = \left(1 + \frac{\theta}{45°}\right)$$

Angle of Channel Turn (θ):	15	deg
Region Type:	Bend	
Correction Factor for Parallel Current (RC):	1.118	

(AASHTO LRFD 3.14.5.2.3-5)

$$R_C = \left(1 + \frac{V_C}{10}\right)$$

Velocity of Parallel Current (VC):	1.185	knots
Correction Factor for Perpendicular Current (RXC):	1.593	

(AASHTO LRFD 3.14.5.2.3-6)

$$R_{XC} = (1 + V_{XC})$$

Velocity of Perpendicuar Current (VXC):	0.593	knots
Correction Factor for Traffic Density (RD):	1	
Traffic Density:	Low	

Page 6

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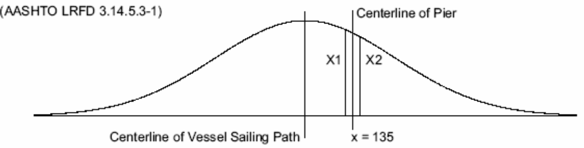
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Geometric Probability Calculations (V1-P1):

Geometric Probability (PG):	0.053714	1/Yrs

(AASHTO LRFD 3.14.5.3-1)



$$PG = NSD(Z2) - NSD(Z1)$$

Normal Standard Distribution at Z1 (NSD(Z1)):	0.673	
Z1:	0.448	
Normal Standard Distribution at Z2 (NSD(Z2)):	0.727	
Z2:	0.603	

$$X_1 = x - \left(\frac{B_P}{2} + \frac{B_M}{2}\right) \qquad X_2 = x + \left(\frac{B_P}{2} + \frac{B_M}{2}\right)$$

$$Z_1 = \frac{X_1}{LOA} \qquad Z_2 = \frac{X_2}{LOA}$$

Impact Pier Width (BP):	4.75	ft

$$B_P = PierWidth \times \cos(\phi) + PierDepth \times \sin(\phi)$$

Pier Width:	4.75	ft
Pier Depth:	4.75	ft
Pier Angle (ϕ):	0	deg
Vessel Width (BM):	35	ft
Vessel Length Over All (LOA):	257	ft
Distance From Pier CL to Bridge CL (x):	135	ft
User Pier x Distance:	-135	ft
User Center Line x Distance:	0	ft

$$x = |UserPier - UserCL|$$

Page 7

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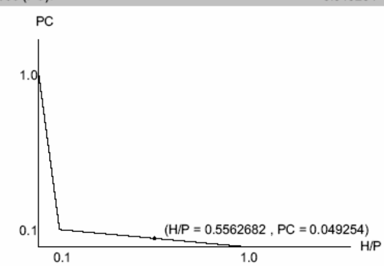
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P1):

Probability of Collapse (PC):	0.049254	1/Yrs



(AASHTO LRFD 3.14.5.4-1)

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right)$$

Ultimate Bridge Element Strength (H):	997	kips
Vessel Impact Force (P):	1792.301	kips
Kinetic Energy (KE):	5367.421	kip - ft

(AASHTO LRFD 3.14.7-1)

$$KE = \frac{C_H W V^2}{29.2}$$

Vessel Displacement Tonnage (W):	1542.214	tonne
Hydrodynamic Mass Coefficient (CH):	1.05	
Draft:	9	ft
Underkeel Clearence:	21.7	ft
Draft:	9	ft
Channel Depth:	30.7	ft
User Channel Elevation:	6	ft
User High Water Line:	36.7	ft

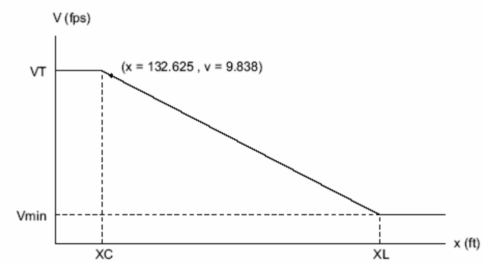
Page 8

VIOB Presented By: The University of Texas at Austin
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P1) (Continued):

Vessel Impact Speed (V):	9.838	ft / s



Typical Vessel Transit Speed in the Channel (VT):	10.127	ft / s
Minimum Design Impact Speed (VMin):	1.688	ft / s
Distance from Chan. Edge to Vessel Path (XC):	110	ft
Channel Width:	220	ft
3 LOA (XL):	771	ft
Distance From Pier Face to Bridge CL (x):	132.625	ft

Page 9

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The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P1) (Continued):

Ship Collision Force on Pier (PS):	NA	kips

(AASHTO LRFD 3.14.8-1)

$$P_S = 8.15V\sqrt{DWT}$$

Deadweight Tonnage of Ship (DWT):	NA	tonne
Vessel Impact Speed (V):	9.838	ft / s
Ship Damage Depth (AS):	NA	ft

(AASHTO LRFD 3.14.9-1)

$$a_S = 1.54\left(\frac{KE}{P_S}\right)$$

Kinetic Energy (KE):	5367.421	kip - ft
Ship Collision Force on Pier (PS):	NA	kips
Barge Collision Force on Pier (PB):	1792.301	kips

(AASHTO LRFD 3.14.11-2)

$$P_B = 1349 + 110a_B$$

Barge Damage Depth (AB):	4.03	ft

(AASHTO LRFD 3.14.12-1)

$$a_B = 10.2\left(\sqrt{1+\frac{KE}{5672}} - 1\right)$$

Kinetic Energy (KE):	5367.421	kip - ft

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The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Vessel 1 - Pier 2

Vessel Frequency Calculations (V1-P2):

Projected Vessel Frequency (N):	812.4	Trips/Yr
Current Vessel Frequency:	677	Trips/Yr
Growth Factor:	1.2	

Probability of Aberrancy Calculations (V1-P2):

Probability of Aberrancy (PA):	0.000285	1/Yrs

(AASHTO LRFD 3.14.5.2.3-1)

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

Aberrancy Base Rate (BR):	0.00012	
Correction Factor for Bridge Location (RB):	1.333	

(AASHTO LRFD 3.14.5.2.3-4)

$$R_B = \left(1 + \frac{\theta}{45°}\right)$$

Angle of Channel Turn (θ):	15	deg
Region Type:	Bend	
Correction Factor for Parallel Current (RC):	1.118	

(AASHTO LRFD 3.14.5.2.3-5)

$$R_C = \left(1 + \frac{V_C}{10}\right)$$

Velocity of Parallel Current (VC):	1.185	knots
Correction Factor for Perpendicular Current (RXC):	1.593	

(AASHTO LRFD 3.14.5.2.3-6)

$$R_{XC} = (1 + V_{XC})$$

Velocity of Perpendicuar Current (VXC):	0.593	knots
Correction Factor for Traffic Density (RD):	1	
Traffic Density:	Low	

VIOB Presented By: The University of Texas at Austin

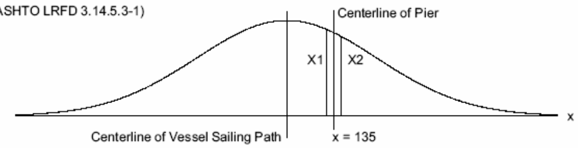
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Geometric Probability Calculations (V1-P2):

Geometric Probability (PG):	0.053714	1/Yrs

(AASHTO LRFD 3.14.5.3-1)



$$PG = NSD(Z2) - NSD(Z1)$$

Normal Standard Distribution at Z1 (NSD(Z1)):	0.673	
Z1:	0.448	
Normal Standard Distribution at Z2 (NSD(Z2)):	0.727	
Z2:	0.603	

$$X_1 = x - \left(\frac{B_P}{2} + \frac{B_M}{2}\right) \qquad X_2 = x + \left(\frac{B_P}{2} + \frac{B_M}{2}\right)$$

$$Z_1 = \frac{X_1}{LOA} \qquad Z_2 = \frac{X_2}{LOA}$$

Impact Pier Width (BP):	4.75	ft

$$B_P = PierWidth \times \cos(\phi) + PierDepth \times \sin(\phi)$$

Pier Width:	4.75	ft
Pier Depth:	4.75	ft
Pier Angle (ϕ):	0	deg
Vessel Width (BM):	35	ft
Vessel Length Over All (LOA):	257	ft
Distance From Pier CL to Bridge CL (x):	135	ft
User Pier x Distance:	135	ft
User Center Line x Distance:	0	ft

$$x = |UserPier - UserCL|$$

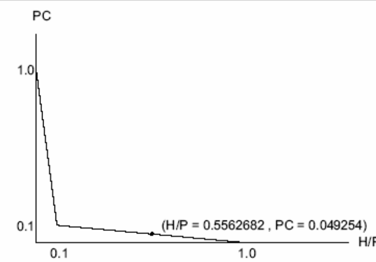
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P2):

Probability of Collapse (PC):	0.049254	1/Yrs



(AASHTO LRFD 3.14.5.4-1)

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right)$$

Ultimate Bridge Element Strength (H):	997	kips
Vessel Impact Force (P):	1792.301	kips
Kinetic Energy (KE):	5367.421	kip - ft

(AASHTO LRFD 3.14.7-1)

$$KE = \frac{C_H W V^2}{29.2}$$

Vessel Displacement Tonnage (W):	1542.214	tonne
Hydrodynamic Mass Coefficient (CH):	1.05	
Draft:	9	ft
Underkeel Clearence:	27.7	ft
Draft:	9	ft
Channel Depth:	36.7	ft
User Channel Elevation:	0	ft
User High Water Line:	36.7	ft

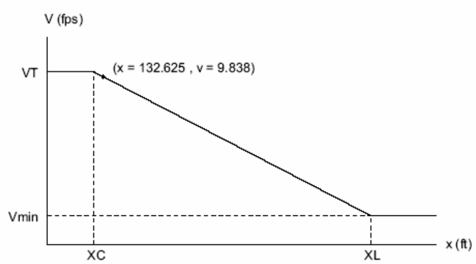
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P2) (Continued):

Vessel Impact Speed (V):	9.838	ft / s



Typical Vessel Transit Speed in the Channel (VT):	10.127	ft / s
Minimum Design Impact Speed (VMin):	1.688	ft / s
Distance from Chan. Edge to Vessel Path (XC):	110	ft
Channel Width:	220	ft
3 LOA (XL):	771	ft
Distance From Pier Face to Bridge CL (x):	132.625	ft

Page 14

VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P2) (Continued):

Ship Collision Force on Pier (PS):	NA	kips

(AASHTO LRFD 3.14.8-1)

$$P_S = 8.15V\sqrt{DWT}$$

Deadweight Tonnage of Ship (DWT):	NA	tonne
Vessel Impact Speed (V):	9.838	ft / s
Ship Damage Depth (AS):	NA	ft

(AASHTO LRFD 3.14.9-1)

$$a_S = 1.54\left(\frac{KE}{P_S}\right)$$

Kinetic Energy (KE):	5367.421	kip - ft
Ship Collision Force on Pier (PS):	NA	kips
Barge Collision Force on Pier (PB):	1792.301	kips

(AASHTO LRFD 3.14.11-2)

$$P_B = 1349 + 110a_B$$

Barge Damage Depth (AB):	4.03	ft

(AASHTO LRFD 3.14.12-1)

$$a_B = 10.2\left(\sqrt{1+\frac{KE}{5672}} - 1\right)$$

Kinetic Energy (KE):	5367.421	kip - ft

Page 15

VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Vessel 1 - Pier 3

Vessel Frequency Calculations (V1-P3):

Projected Vessel Frequency (N):	812.4	Trips/Yr
Current Vessel Frequency:	677	Trips/Yr
Growth Factor:	1.2	

Probability of Aberrancy Calculations (V1-P3):

Probability of Aberrancy (PA):	0.000285	1/Yrs

(AASHTO LRFD 3.14.5.2.3-1)

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

Aberrancy Base Rate (BR):	0.00012	
Correction Factor for Bridge Location (RB):	1.333	

(AASHTO LRFD 3.14.5.2.3-4)

$$R_B = \left(1 + \frac{\theta}{45°}\right)$$

Angle of Channel Turn (θ):	15	deg
Region Type:	Bend	
Correction Factor for Parallel Current (RC):	1.118	

(AASHTO LRFD 3.14.5.2.3-5)

$$R_C = \left(1 + \frac{V_C}{10}\right)$$

Velocity of Parallel Current (VC):	1.185	knots
Correction Factor for Perpendicular Current (RXC):	1.593	

(AASHTO LRFD 3.14.5.2.3-6)

$$R_{XC} = (1 + V_{XC})$$

Velocity of Perpendicuar Current (VXC):	0.593	knots
Correction Factor for Traffic Density (RD):	1	
Traffic Density:	Low	

VIOB Presented By: The University of Texas at Austin

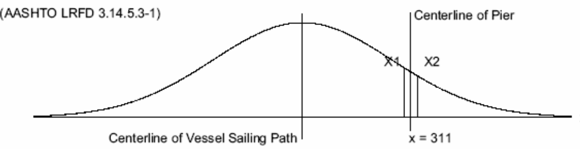
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Geometric Probability Calculations (V1-P3):

Geometric Probability (PG):	0.028937	1/Yrs

(AASHTO LRFD 3.14.5.3-1)



$$PG = NSD(Z2) - NSD(Z1)$$

Normal Standard Distribution at Z1 (NSD(Z1)):	0.872	
Z1:	1.135	
Normal Standard Distribution at Z2 (NSD(Z2)):	0.901	
Z2:	1.286	

$$X_1 = x - \left(\frac{B_P}{2} + \frac{B_M}{2}\right) \qquad X_2 = x + \left(\frac{B_P}{2} + \frac{B_M}{2}\right)$$

$$Z_1 = \frac{X_1}{LOA} \qquad Z_2 = \frac{X_2}{LOA}$$

Impact Pier Width (BP):	3.75	ft

$$B_P = PierWidth \times \cos(\phi) + PierDepth \times \sin(\phi)$$

Pier Width:	3.75	ft
Pier Depth:	3.75	ft
Pier Angle (ϕ):	0	deg
Vessel Width (BM):	35	ft
Vessel Length Over All (LOA):	257	ft
Distance From Pier CL to Bridge CL (x):	311	ft
User Pier x Distance:	311	ft
User Center Line x Distance:	0	ft

$$x = |UserPier - UserCL|$$

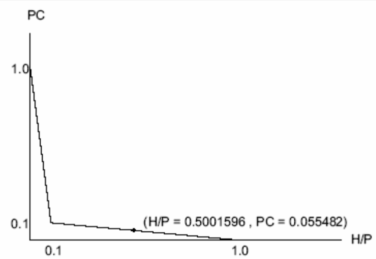
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P3):

Probability of Collapse (PC):	0.055482	1/Yrs



(AASHTO LRFD 3.14.5.4-1)

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right)$$

Ultimate Bridge Element Strength (H):	815	kips
Vessel Impact Force (P):	1629.48	kips
Kinetic Energy (KE):	3190.247	kip - ft

(AASHTO LRFD 3.14.7-1)

$$KE = \frac{C_H W V^2}{29.2}$$

Vessel Displacement Tonnage (W):	1542.214	tonne
Hydrodynamic Mass Coefficient (CH):	1.05	
Draft:	9	ft
Underkeel Clearence:	11.7	ft
Draft:	9	ft
Channel Depth:	20.7	ft
User Channel Elevation:	16	ft
User High Water Line:	36.7	ft

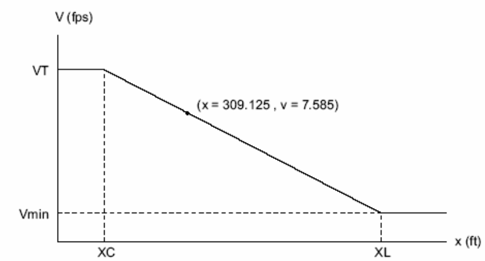
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P3) (Continued):

Vessel Impact Speed (V):	7.585	ft / s



Typical Vessel Transit Speed in the Channel (VT):	10.127	ft / s
Minimum Design Impact Speed (VMin):	1.688	ft / s
Distance from Chan. Edge to Vessel Path (XC):	110	ft
Channel Width:	220	ft
3 LOA (XL):	771	ft
Distance From Pier Face to Bridge CL (x):	309.125	ft

Detailed Calculations (Continued):

Probability of Collapse Calculations (V1-P3) (Continued):

Ship Collision Force on Pier (PS):	NA	kips

(AASHTO LRFD 3.14.8-1)

$$P_S = 8.15V\sqrt{DWT}$$

Deadweight Tonnage of Ship (DWT):	NA	tonne
Vessel Impact Speed (V):	7.585	ft / s
Ship Damage Depth (AS):	NA	ft

(AASHTO LRFD 3.14.9-1)

$$a_S = 1.54\left(\frac{KE}{P_S}\right)$$

Kinetic Energy (KE):	3190.247	kip - ft
Ship Collision Force on Pier (PS):	NA	kips
Barge Collision Force on Pier (PB):	1629.48	kips

(AASHTO LRFD 3.14.11-2)

$$P_B = 1349 + 110a_B$$

Barge Damage Depth (AB):	2.55	ft

(AASHTO LRFD 3.14.12-1)

$$a_B = 10.2\left(\sqrt{1+\frac{KE}{5672}} - 1\right)$$

Kinetic Energy (KE):	3190.247	kip - ft

VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Vessel 2 - Pier 1

Vessel Frequency Calculations (V2-P1):

Projected Vessel Frequency (N):	812.4	Trips/Yr
Current Vessel Frequency:	677	Trips/Yr
Growth Factor:	1.2	

Probability of Aberrancy Calculations (V2-P1):

Probability of Aberrancy (PA):	0.000285	1/Yrs

(AASHTO LRFD 3.14.5.2.3-1)

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

Aberrancy Base Rate (BR):	0.00012	
Correction Factor for Bridge Location (RB):	1.333	

(AASHTO LRFD 3.14.5.2.3-4)

$$R_B = \left(1 + \frac{\theta}{45°}\right)$$

Angle of Channel Turn (θ):	15	deg
Region Type:	Bend	
Correction Factor for Parallel Current (RC):	1.118	

(AASHTO LRFD 3.14.5.2.3-5)

$$R_C = \left(1 + \frac{V_C}{10}\right)$$

Velocity of Parallel Current (VC):	1.185	knots
Correction Factor for Perpendicular Current (RXC):	1.593	

(AASHTO LRFD 3.14.5.2.3-6)

$$R_{XC} = (1 + V_{XC})$$

Velocity of Perpendicuar Current (VXC):	0.593	knots
Correction Factor for Traffic Density (RD):	1	
Traffic Density:	Low	

VIOB Presented By: The University of Texas at Austin

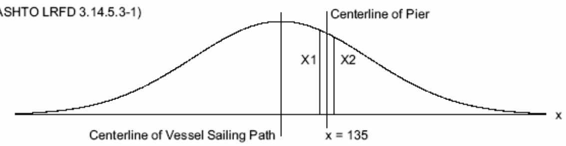
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Geometric Probability Calculations (V2-P1):

Geometric Probability (PG):	0.053714	1/Yrs

(AASHTO LRFD 3.14.5.3-1)



$$PG = NSD(Z2) - NSD(Z1)$$

Normal Standard Distribution at Z1 (NSD(Z1)):	0.673	
Z1:	0.448	
Normal Standard Distribution at Z2 (NSD(Z2)):	0.727	
Z2:	0.603	

$$X_1 = x - \left(\frac{B_P}{2} + \frac{B_M}{2}\right) \qquad X_2 = x + \left(\frac{B_P}{2} + \frac{B_M}{2}\right)$$

$$Z_1 = \frac{X_1}{LOA} \qquad Z_2 = \frac{X_2}{LOA}$$

Impact Pier Width (BP):	4.75	ft

$$B_P = PierWidth \times \cos(\phi) + PierDepth \times \sin(\phi)$$

Pier Width:	4.75	ft
Pier Depth:	4.75	ft
Pier Angle (ϕ):	0	deg
Vessel Width (BM):	35	ft
Vessel Length Over All (LOA):	257	ft
Distance From Pier CL to Bridge CL (x):	135	ft
User Pier x Distance:	-135	ft
User Center Line x Distance:	0	ft

$$x = \left|UserPier - UserCL\right|$$

Page 22

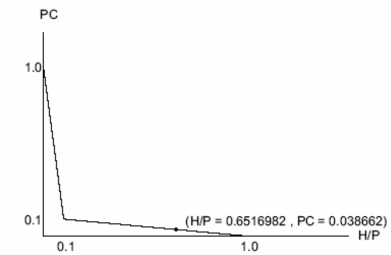
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P1):

Probability of Collapse (PC):	0.038662	1/Yrs



(AASHTO LRFD 3.14.5.4-1)

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right)$$

Ultimate Bridge Element Strength (H):	997	kips
Vessel Impact Force (P):	1529.849	kips
Kinetic Energy (KE):	1975.842	kip - ft

(AASHTO LRFD 3.14.7-1)

$$KE = \frac{C_H W V^2}{29.2}$$

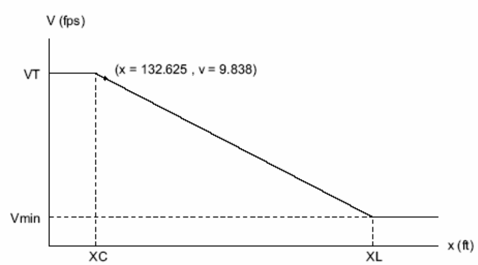
Vessel Displacement Tonnage (W):	567.716	tonne
Hydrodynamic Mass Coefficient (CH):	1.05	
Draft:	9	ft
Underkeel Clearence:	21.7	ft
Draft:	9	ft
Channel Depth:	30.7	ft
User Channel Elevation:	6	ft
User High Water Line:	36.7	ft

Page 23

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P1) (Continued):

Vessel Impact Speed (V):	9.838	ft / s



Typical Vessel Transit Speed in the Channel (VT):	10.127	ft / s
Minimum Design Impact Speed (VMin):	1.688	ft / s
Distance from Chan. Edge to Vessel Path (XC):	110	ft
Channel Width:	220	ft
3 LOA (XL):	771	ft
Distance From Pier Face to Bridge CL (x):	132.625	ft

VIOB Presented By: The University of Texas at Austin
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P1) (Continued):

Ship Collision Force on Pier (PS):	NA	kips

(AASHTO LRFD 3.14.8-1)

$$P_S = 8.15V\sqrt{DWT}$$

Deadweight Tonnage of Ship (DWT):	NA	tonne
Vessel Impact Speed (V):	9.838	ft / s
Ship Damage Depth (AS):	NA	ft

(AASHTO LRFD 3.14.9-1)

$$a_S = 1.54\left(\frac{KE}{P_S}\right)$$

Kinetic Energy (KE):	1975.842	kip - ft
Ship Collision Force on Pier (PS):	NA	kips
Barge Collision Force on Pier (PB):	1529.849	kips

(AASHTO LRFD 3.14.11-2)

$$P_B = 1349 + 110a_B$$

Barge Damage Depth (AB):	1.644	ft

(AASHTO LRFD 3.14.12-1)

$$a_B = 10.2\left(\sqrt{1+\frac{KE}{5672}} - 1\right)$$

Kinetic Energy (KE):	1975.842	kip - ft

VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Vessel 2 - Pier 2

Vessel Frequency Calculations (V2-P2):

Projected Vessel Frequency (N):	812.4	Trips/Yr
Current Vessel Frequency:	677	Trips/Yr
Growth Factor:	1.2	

Probability of Aberrancy Calculations (V2-P2):

Probability of Aberrancy (PA):	0.000285	1/Yrs

(AASHTO LRFD 3.14.5.2.3-1)

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

Aberrancy Base Rate (BR):	0.00012	
Correction Factor for Bridge Location (RB):	1.333	

(AASHTO LRFD 3.14.5.2.3-4)

$$R_B = \left(1 + \frac{\theta}{45°}\right)$$

Angle of Channel Turn (θ):	15	deg
Region Type:	Bend	
Correction Factor for Parallel Current (RC):	1.118	

(AASHTO LRFD 3.14.5.2.3-5)

$$R_C = \left(1 + \frac{V_C}{10}\right)$$

Velocity of Parallel Current (VC):	1.185	knots
Correction Factor for Perpendicular Current (RXC):	1.593	

(AASHTO LRFD 3.14.5.2.3-6)

$$R_{XC} = (1 + V_{XC})$$

Velocity of Perpendicuar Current (VXC):	0.593	knots
Correction Factor for Traffic Density (RD):	1	
Traffic Density:	Low	

VIOB Presented By: The University of Texas at Austin

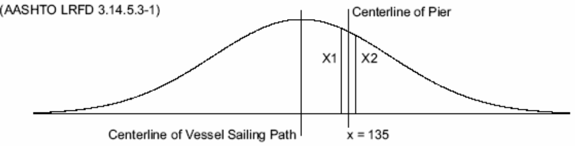
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Geometric Probability Calculations (V2-P2):

Geometric Probability (PG):	0.053714	1/Yrs

(AASHTO LRFD 3.14.5.3-1)



$$PG = NSD(Z2) - NSD(Z1)$$

Normal Standard Distribution at Z1 (NSD(Z1)):	0.673	
Z1:	0.448	
Normal Standard Distribution at Z2 (NSD(Z2)):	0.727	
Z2:	0.603	

$$X_1 = x - \left(\frac{B_P}{2} + \frac{B_M}{2}\right) \qquad X_2 = x + \left(\frac{B_P}{2} + \frac{B_M}{2}\right)$$

$$Z_1 = \frac{X_1}{LOA} \qquad Z_2 = \frac{X_2}{LOA}$$

Impact Pier Width (BP):	4.75	ft

$$B_P = PierWidth \times \cos(\phi) + PierDepth \times \sin(\phi)$$

Pier Width:	4.75	ft
Pier Depth:	4.75	ft
Pier Angle (ϕ):	0	deg
Vessel Width (BM):	35	ft
Vessel Length Over All (LOA):	257	ft
Distance From Pier CL to Bridge CL (x):	135	ft
User Pier x Distance:	135	ft
User Center Line x Distance:	0	ft

$$x = |UserPier - UserCL|$$

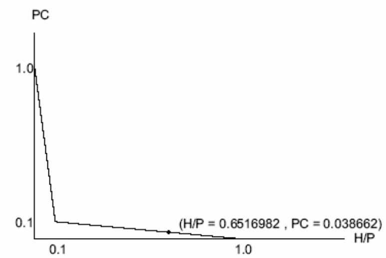
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P2):

Probability of Collapse (PC):	0.038662	1/Yrs



(AASHTO LRFD 3.14.5.4-1)

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right)$$

Ultimate Bridge Element Strength (H):	997	kips
Vessel Impact Force (P):	1529.849	kips
Kinetic Energy (KE):	1975.842	kip - ft

(AASHTO LRFD 3.14.7-1)

$$KE = \frac{C_H W V^2}{29.2}$$

Vessel Displacement Tonnage (W):	567.716	tonne
Hydrodynamic Mass Coefficient (CH):	1.05	
Draft:	9	ft
Underkeel Clearence:	27.7	ft
Draft:	9	ft
Channel Depth:	36.7	ft
User Channel Elevation:	0	ft
User High Water Line:	36.7	ft

Page 28

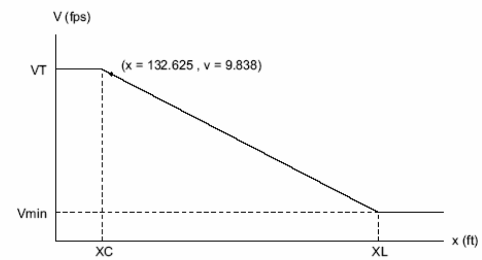
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P2) (Continued):

Vessel Impact Speed (V):	9.838	ft / s



Typical Vessel Transit Speed in the Channel (VT):	10.127	ft / s
Minimum Design Impact Speed (VMin):	1.688	ft / s
Distance from Chan. Edge to Vessel Path (XC):	110	ft
Channel Width:	220	ft
3 LOA (XL):	771	ft
Distance From Pier Face to Bridge CL (x):	132.625	ft

Page 29

VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P2) (Continued):

Ship Collision Force on Pier (PS):	NA	kips

(AASHTO LRFD 3.14.8-1)

$$P_S = 8.15V\sqrt{DWT}$$

Deadweight Tonnage of Ship (DWT):	NA	tonne
Vessel Impact Speed (V):	9.838	ft / s
Ship Damage Depth (AS):	NA	ft

(AASHTO LRFD 3.14.9-1)

$$a_S = 1.54\left(\frac{KE}{P_S}\right)$$

Kinetic Energy (KE):	1975.842	kip - ft
Ship Collision Force on Pier (PS):	NA	kips
Barge Collision Force on Pier (PB):	1529.849	kips

(AASHTO LRFD 3.14.11-2)

$$P_B = 1349 + 110a_B$$

Barge Damage Depth (AB):	1.644	ft

(AASHTO LRFD 3.14.12-1)

$$a_B = 10.2\left(\sqrt{1+\frac{KE}{5672}} - 1\right)$$

Kinetic Energy (KE):	1975.842	kip - ft

VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Vessel 2 - Pier 3

Vessel Frequency Calculations (V2-P3):

Projected Vessel Frequency (N):	812.4	Trips/Yr
Current Vessel Frequency:	677	Trips/Yr
Growth Factor:	1.2	

Probability of Aberrancy Calculations (V2-P3):

Probability of Aberrancy (PA):	0.000285	1/Yrs

(AASHTO LRFD 3.14.5.2.3-1)

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

Aberrancy Base Rate (BR):	0.00012	
Correction Factor for Bridge Location (RB):	1.333	

(AASHTO LRFD 3.14.5.2.3-4)

$$R_B = \left(1 + \frac{\theta}{45°}\right)$$

Angle of Channel Turn (θ):	15	deg
Region Type:	Bend	
Correction Factor for Parallel Current (RC):	1.118	

(AASHTO LRFD 3.14.5.2.3-5)

$$R_C = \left(1 + \frac{V_C}{10}\right)$$

Velocity of Parallel Current (VC):	1.185	knots
Correction Factor for Perpendicular Current (RXC):	1.593	

(AASHTO LRFD 3.14.5.2.3-6)

$$R_{XC} = (1 + V_{XC})$$

Velocity of Perpendicuar Current (VXC):	0.593	knots
Correction Factor for Traffic Density (RD):	1	
Traffic Density:	Low	

VIOB Presented By: The University of Texas at Austin

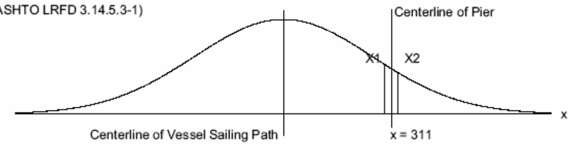
The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Geometric Probability Calculations (V2-P3):

Geometric Probability (PG):	0.028937	1/Yrs

(AASHTO LRFD 3.14.5.3-1)



$$PG = NSD(Z2) - NSD(Z1)$$

Normal Standard Distribution at Z1 (NSD(Z1)):	0.872	
Z1:	1.135	
Normal Standard Distribution at Z2 (NSD(Z2)):	0.901	
Z2:	1.286	

$$X_1 = x - \left(\frac{B_P}{2} + \frac{B_M}{2}\right) \qquad X_2 = x + \left(\frac{B_P}{2} + \frac{B_M}{2}\right)$$

$$Z_1 = \frac{X_1}{LOA} \qquad Z_2 = \frac{X_2}{LOA}$$

Impact Pier Width (BP):	3.75	ft

$$B_P = PierWidth \times \cos(\phi) + PierDepth \times \sin(\phi)$$

Pier Width:	3.75	ft
Pier Depth:	3.75	ft
Pier Angle (ϕ):	0	deg
Vessel Width (BM):	35	ft
Vessel Length Over All (LOA):	257	ft
Distance From Pier CL to Bridge CL (x):	311	ft
User Pier x Distance:	311	ft
User Center Line x Distance:	0	ft

$$x = |UserPier - UserCL|$$

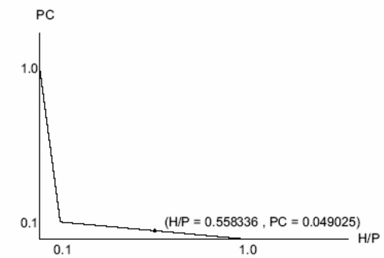
VIOB Presented By: The University of Texas at Austin

The Next Generation of Analysis for Vessel Impact on Bridges

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P3):

Probability of Collapse (PC):	0.049025	1/Yrs



(AASHTO LRFD 3.14.5.4-1)

$$PC = 0.1 + 9\left(0.1 - \frac{H}{P}\right)$$

Ultimate Bridge Element Strength (H):	815	kips
Vessel Impact Force (P):	1459.694	kips
Kinetic Energy (KE):	1174.386	kip - ft

(AASHTO LRFD 3.14.7-1)

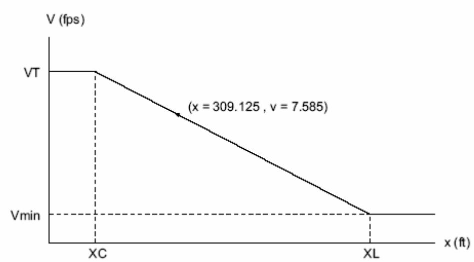
$$KE = \frac{C_H W V^2}{29.2}$$

Vessel Displacement Tonnage (W):	567.716	tonne
Hydrodynamic Mass Coefficient (CH):	1.05	
Draft:	9	ft
Underkeel Clearence:	11.7	ft
Draft:	9	ft
Channel Depth:	20.7	ft
User Channel Elevation:	16	ft
User High Water Line:	36.7	ft

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P3) (Continued):

Vessel Impact Speed (V):	7.585	ft / s



Typical Vessel Transit Speed in the Channel (VT):	10.127	ft / s
Minimum Design Impact Speed (VMin):	1.688	ft / s
Distance from Chan. Edge to Vessel Path (XC):	110	ft
Channel Width:	220	ft
3 LOA (XL):	771	ft
Distance From Pier Face to Bridge CL (x):	309.125	ft

Detailed Calculations (Continued):

Probability of Collapse Calculations (V2-P3) (Continued):

Ship Collision Force on Pier (PS):	NA	kips

(AASHTO LRFD 3.14.8-1)

$$P_S = 8.15V\sqrt{DWT}$$

Deadweight Tonnage of Ship (DWT):	NA	tonne
Vessel Impact Speed (V):	7.585	ft / s
Ship Damage Depth (AS):	NA	ft

(AASHTO LRFD 3.14.9-1)

$$a_S = 1.54\left(\frac{KE}{P_S}\right)$$

Kinetic Energy (KE):	1174.386	kip - ft
Ship Collision Force on Pier (PS):	NA	kips
Barge Collision Force on Pier (PB):	1459.695	kips

(AASHTO LRFD 3.14.11-2)

$$P_B = 1349 + 110a_B$$

Barge Damage Depth (AB):	1.006	ft

(AASHTO LRFD 3.14.12-1)

$$a_B = 10.2\left(\sqrt{1+\frac{KE}{5672}} - 1\right)$$

Kinetic Energy (KE):	1174.386	kip - ft

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