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Technical Letter
No. 1110-2-563 30 September 2004

Engineering and Design
BARGE IMPACT ANALYSIS FOR RIGID WALLS

1. Purpose. This engineer technical letter (ETL) provides guidance for design and evaluation of barge impact loading on rigid navigation structures such as lock walls, approach walls, channel walls, revetments, and coastal structures. This ETL is applicable to barge impact angles less than 30 degrees (glancing) and is not applicable for broadside or direct (head-on) impacts and is not intended for flexible structures.

2. Applicability. This ETL applies to HQUSACE elements, major subordinate commands, districts, laboratories, and separate field operating activities having responsibilities for the design and evaluation of civil works projects.

3. Distribution Statement. Approved for public release; distribution is unlimited.

4. References. References are listed in Appendix A.

5. Background/Discussion.

a. The barge impact loads defined in EM 1110-2-2602 are very limited in scope. Therefore since 1993, U.S. Army Corps of Engineers (USACE) navigation structures have been designed and evaluated using the methods defined in ETL 1110-2-338, Barge Impact Analysis, 30 April 1993. This ETL was rescinded 30 July 1999. During the design of several recent lock projects, it became apparent that a more realistic and thorough design method was required. The impact values calculated from the methods presented in ETL 1110-2-338 were too conservative for design. The existing analytical model in ETL 1110-2-338 used for the analysis of barge impact loads uses a method that assumed crushing of the barge hull would occur during every collision with an approach wall. Therefore, under the Innovations for Navigation Projects Research and Development Program, a series of full-scale barge impact experiments (Patev, Barker, and Koestler 2003a, 2003b) was conducted to capture the normal force of a barge impacting a rigid lock wall.

b. This ETL will furnish engineering guidance for the development of barge impact forces to be used in the design of rigid walls at USACE navigation projects. This guidance is based on the results of full-scale experiments as described in Patev, Barker, and Koestler (2003a, 2003b). An empirical method (Arroyo, Ebeling, and Barker 2003) has been developed to estimate the barge impact forces for use in the design and evaluation of rigid structures.

c. The empirical method of Arroyo, Ebeling, and Barker (2003) given in this ETL uses the mass, approach angle, and the forward and lateral velocities of the barge train as the input parameters to the model. This empirical method was based on a limited number of low-velocity, full-scale experiments as described in Patev, Barker, and Koestler (2003a, 2003b) and Arroyo, Ebeling, and Barker (2003), and is limited to impact forces less than 3,558 kN (800 kips).

d. Probabilistic Barge Impact Analysis (PBIA) as presented in Appendices C and D should be used to estimate the relative frequency of different impact magnitudes and the corresponding return period for given design events (i.e., usual, unusual, and extreme load cases).

6. Action. The enclosed guidance should be used to estimate the barge impact forces on rigid navigation structures.

FOR THE DIRECTOR OF CIVIL WORKS:

DONALD L. BASHAM, PE
Chief, Engineering & Construction
Directorate of Civil Works

6 Appendixes
A – References
B – Design Guidance for Barge Impact Loads on Rigid Walls
C – Data from Previous Studies
D – Examples of Probabilistic Barge Impact Analysis (PBIA) for Rigid Walls
E – Empirical Method for Barge Impact Analysis for Rigid Walls
F – Field Experiments

Appendix A
References

EM 1110-2-2104
Strength Design for Reinforced Concrete Hydraulic Structures

EM 1110-2-2602
Planning and Design of Navigation Lock Walls

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Appendix B
Design Guidance for Barge Impact Loads on Rigid Walls

B-1. Introduction

a. Background.

(1) Inland navigation structures are subjected to impact loads due to transiting barge trains. Barge impact forces for rare events such as operator error, loss of power, or loss of control have dramatically influenced the overall costs of navigation structures (Patev 1999). Figure B-1 shows the results of a barge impact on a guard wall bullnose due to a loss of control (extreme) event at Smithland Lock and Dam. The existing analytical model in ETL 1110-2-338 used for the analysis of barge impact loads was too conservative because the method assumed that the barge hull would be crushed in every collision. However, barge hulls are rarely crushed as a result of impacts with navigation lock walls. With the current emphasis to lower project first costs, thin-walled precast structures that can be lifted or floated into place are now being designed; and an accurate estimate of barge impact forces is critical in their design. If some reasonable risk over the service life of a project is accepted, the initial and long-term construction costs can be lowered and the wall design can be optimized to maintain a safe and economical navigation structure. A better understanding of the risks could be gained through decision analyses that include developing trade-offs between the stakeholders' costs, safety, and operational requirements for the navigation projects (Tsang, Lambert, and Patev 2002).

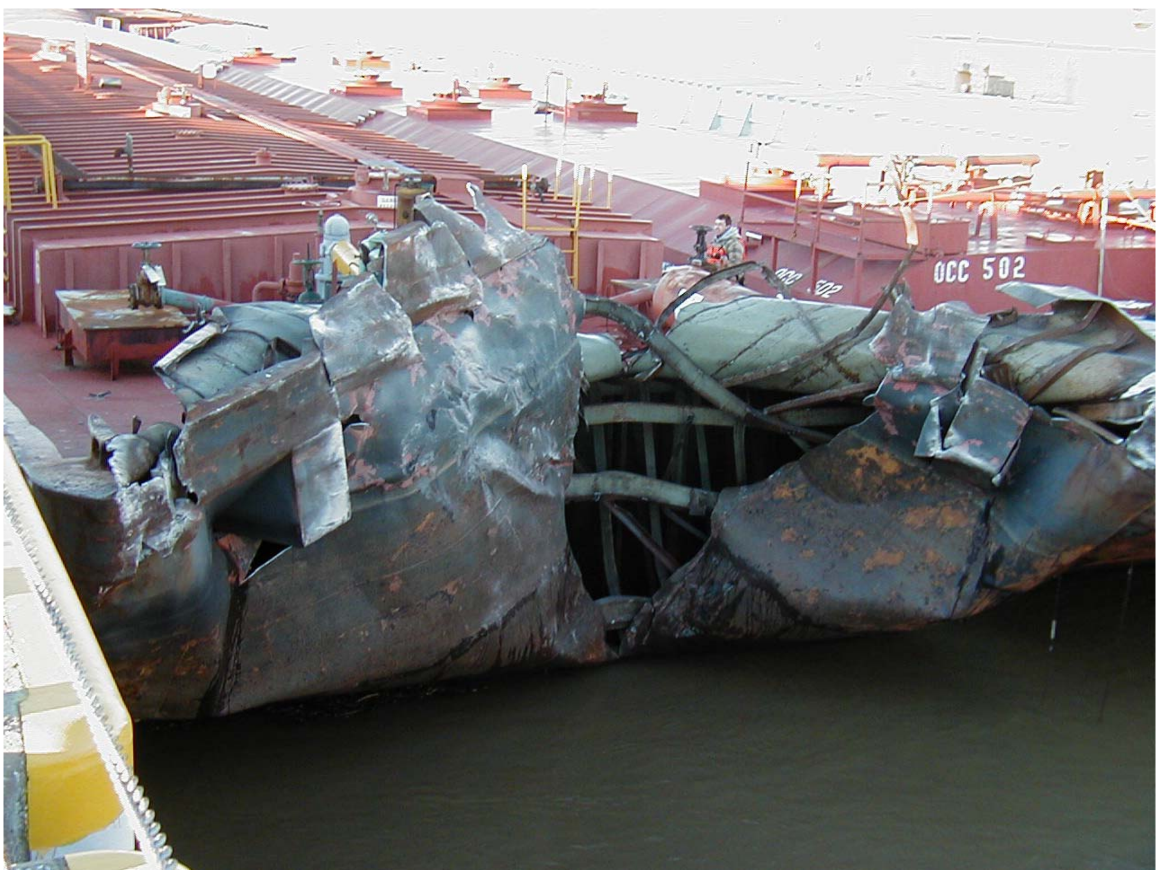

Figure B-1. Barge impact due to loss of control at Smithland Lock and Dam

(2) The previous USACE barge impact design methodology for inland navigation structures is discussed in ETL 1110-2-338. The response of the barges and wall is modeled as a two-degree-of-freedom (TDOF) system as shown in Figure B-2 where *K* is the stiffness, *M* is the mass, *V* is velocity, and θ is the approach angle. The input required to this TDOF model is the mass, size (width and length), approach velocity, and angle of impact of the barge train. The model was developed for both rigid and flexible structures and was based on a constant pressure coefficient developed by Minorsky (1959). This Minorsky model relates the kinetic energy lost during impact to the damage sustained during collisions of deep-draft vessels, and assumes that permanent deformation and penetration will occur during crushing of the vessel hull.

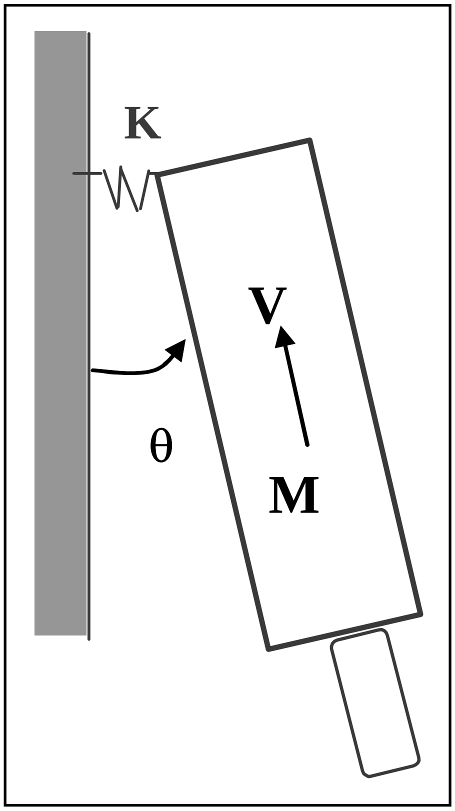

Figure B-2. Two-Degree-of-Freedom barge train-wall system (Patev 1999)

(3) However, the model developed in ETL 1110-2-338 had significant limitations. First, the existing TDOF model did not account for the flexibility of the barge train during impact on a navigation structure. This flexibility is caused by the lashings (or wire ropes) that tie the barges together and is a mechanism for absorption of energy within the mass of the barge train. Figure B-3 shows an example of deck lashing for an internal connection. An improved model from the TDOF is represented by a Multi-Degree-of-Freedom (MDOF) system as shown in Figure B-4 where *K** is the equivalent stiffness, *M** is the equivalent mass, *V* is the velocity, and θ is the approach angle of the barge train.

Figure B-3. Deck lashing (from Patev, Barker, and Koestler 2003a)

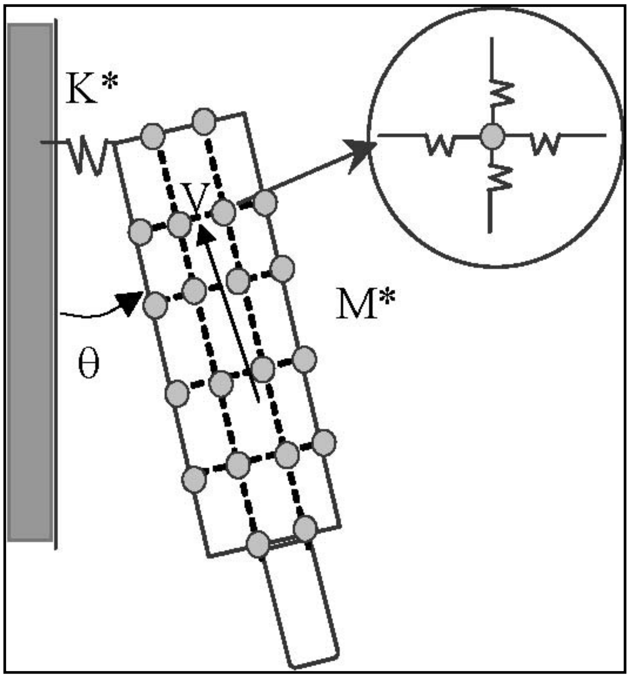

Figure B-4. Multi-Degree-of-Freedom system (from Patev 1999)

(4) Second, the model was based on crushing of the barge corner. Such large deformations are very rarely encountered on the inland waterway during most usual and unusual impact events.

(5) Third, the model utilized a trigonometric function to represent the stiffness function; the function yielded incorrect results for small approach angles (less than 5 degrees) and large angles (greater than 85 degrees). Therefore, this model did not yield realistic results for head-on impacts into bullnoses and protection cells and for estimating the resulting impact forces at small angles. The limitations of this model were primarily the result of applying technology that is appropriate for deep-draft vessels to inland barge trains without field validation. The limitations of the model, combined with the consensus that the model produces conservative design loads, are the primary reasons why USACE performed prototype (Patev, Barker, and Koestler 2003b) and full-scale (Patev, Barker, and Koestler 2003a) barge impact experiments as a basis for improving this method.

b. *Objectives.* This ETL provides the following:

- Information for estimating the masses, approach velocities, and approach angles. Examples of data and distributions for mass, angle, and velocity from recent designs of USACE navigation projects structures are shown in Appendix C.
- Information on return periods for use in probabilistic design of lock walls for barge impact loads are explained through examples in Appendix D.
- A new empirical method (Arroyo, Ebeling, and Barker 2003) for estimating corner impact loads on rigid walls is furnished in Appendix E. This method is based on the results of full-scale experiments described in Appendix F (Patev, Barker, and Koestler 2003a, 2003b).

B-2. Empirical Barge Impact Model

a. Full-scale barge impact experiments were conducted from 1997 to 2000. These experiments were performed to increase understanding of the complex dynamics and failure modes of the barge train system, and to assist in the development of numerical models. No barge damage or lashing failures occurred during the impacts used to develop the empirical correlation. This is not consistent with the Minorsky (1959) model discussed in ETL 1110-2-338. The data used to derive the empirical correlation were limited to barge train velocities up to 0.17 m/sec (0.57 ft/sec) normal to the wall, for impact angles up to 21.1 deg, and for linear momentum normal to the wall between 2.9 and 4.6 MN-sec (650 and 1,025 k-sec). In addition, the experiments indicated that an MDOF system must be used to model the barge train to account for the dynamic response of the lashings. Further details on the experiments and their results are described in Appendix F.

b. Based on the results (Patev, Barker, and Koestler 2003a) and processing of the experiments (Arroyo, Ebeling, and Barker 2003), an empirical correlation has been developed to equate the maximum impact force normal to the wall F_m to the linear momentum of the barge train as it impacts the wall. Figure B-5 shows the data required for the empirical correlation. The results from the

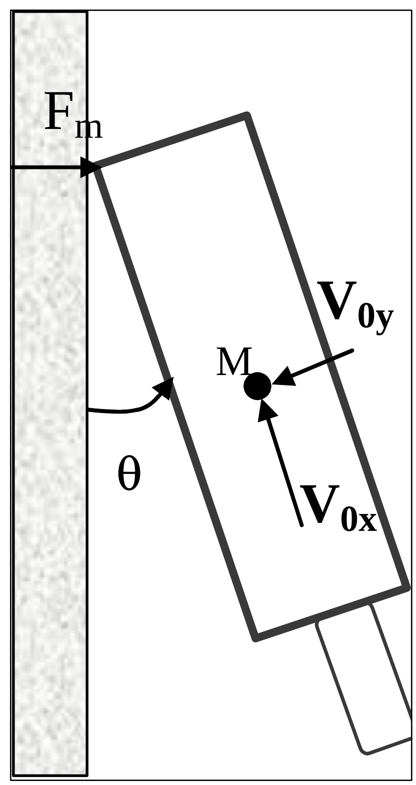

Figure B-5. Data requirements for empirical model

empirical correlation also compare well with a derivation of the mechanical model for the impact of a rigid barge train on a rigid wall.

c. However, based on field observations and limitations of the field data, the values from the empirical correlation are limited to an F_m of less than 3.56 MN (800 kips). The designer should consult with CECW-CE if the value of the maximum impact force exceeds 3.56 MN (800 kips). This limitation is imposed because the equation does not account for the effects of lashing failures or deck buckling of the corner plates under higher impact loads. The empirical correlation is defined as:

$$F_m = 0.435 \cdot m \cdot (V_{0x} \cdot \sin\theta + V_{0y} \cdot \cos\theta)$$
$$F_m \leq 800 \text{ kips}$$

where

V_{0x} = initial longitudinal velocity of barge in x-direction, ft/sec

V_{0y} = initial transverse velocity of barge in y-direction, ft/sec

and

m = mass, kip-sec^2/ft, calculated as

$$m = \frac{2W}{g}$$

where

W = weight of barge train in short tons, including towboat (but excluding hydrodynamic added mass)

2 = conversion factor from short tons to kips

g = 32.2 ft/sec^2

B-3. Return Periods for Barge Impact Analysis

a. *Background*. The ability to define the loads to which a structure will be subjected during its service life is critical in the design of navigation structures. A method of defining load conditions due to barge impacts needs to be defined on a basis equivalent with other loading conditions such as pool levels or seismic events. To accomplish this, the use of the return period or an annual probability has been adopted to design the structure to maintain a certain level of structural performance.

b. *Definition of design events for barge impact*.

(1) The return periods for barge impact can be defined using the following three load condition categories:

- Usual – These loads can be expected to occur frequently during the service life of a structure, and no damage will occur to either the barge or wall. This typically corresponds to a 50 percent chance of being exceeded in any given year.

- Unusual – These loads can be expected to occur infrequently during the service life of a structure, and minor damage can occur to either the barge or wall. This damage is easily repairable without loss of function for the structure or disruption of service to navigation traffic. This typically corresponds to a 50 percent chance of being exceeded within a 100-year service life.

- Extreme – These loads are due to rare events and can be regarded as an emergency condition. Moderate to extreme damage can occur to either the wall or barge without complete collapse of structure (i.e., structure is repairable but with a loss of function or with an extended disruption of service to navigation traffic). This typically corresponds to a 10 percent chance of being exceeded within a 100-year service life.

(2) From these definitions of load condition categories, Table B-1 and Figure B-6 show a guideline for annual probabilities and return periods for barge impact scenarios. The return periods in this table reflect a design life of 50 years and a service life of at least 100 years, including one major rehabilitation during its service life.

Table B-1
Preliminary Level Design Return Periods for Barge Impact

Load Condition Categories	Annual Probability of Exceedence	Return Period
Usual	Greater than or equal to 0.1	1-10 years
Unusual	Less that 0.1 but greater than 0.00333	10-300 years
Extreme	Less than 0.00333	>300 years

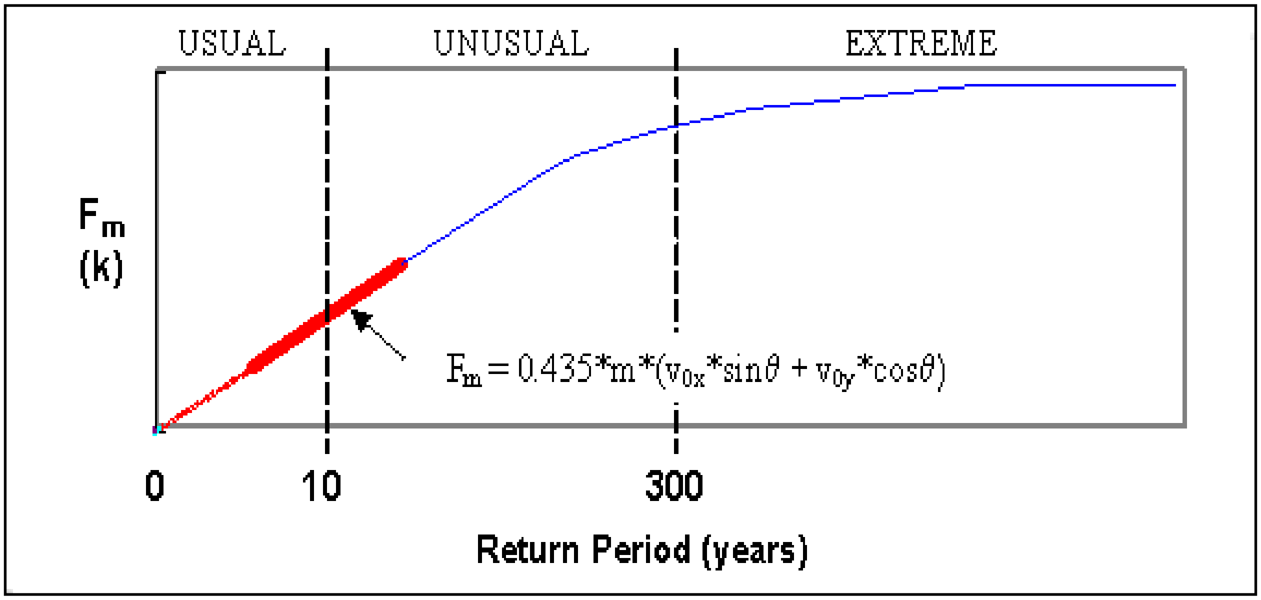

Figure B-6. Impact force versus return period (Note: Range of data processed from the experiments represented by darkened line)

c. Use of Probabilistic Barge Impact Analysis (PBIA) to estimate return periods.

(1) The design or evaluation of rigid walls should be based on a range of barge impact angles and approach velocities that can be realistically expected to occur during its service life. PBIA affords the ability to define the return period based on the probability of possible impact events. The variables used in barge impact analysis require numerous combinations of events that cannot be modeled as a discrete event.

(2) PBIA accounts for the variations of the random variables and empirical model in barge impact design. Coefficients of variations for barge impact forces range from around 10 up to 30 percent depending upon the load condition being considered. The selection of return periods as defined in Table B-1 needs to be tied to the variation of the uncertainties incorporated in the PBIA. The higher the variations in the input for a load condition, the higher range of the return period should be selected accordingly. Appendix D shows a PBIA example and how to select return periods for design.

(3) The PBIA method requires that annual distributions should be determined for mass, impact angle, and approach velocities as well as the uncertainties in the empirical model defined in paragraph B-2. The uncertainties in mass, velocity, and impact angle can be related to the variations of impact load and the likelihood of occurrence of loading conditions by using Monte Carlo simulation software (e.g., @Risk) as described in Appendix D.

(4) Examples of data and distributions for mass, angle, and velocity from recent designs of USACE navigation projects structures are shown in Appendix C. Appendix D shows the deterministic calculations for impact force using the empirical equation as defined above as well as an example for a PBIA for an upper guide wall structure.

B-4. Parameters for Barge Impact

a. Background. It is frequently difficult to estimate the range or distributions of masses, approach velocities, and angles used in the PBIA. This range should include angles and velocities caused by a loss of power and control, as well as any anticipated future changes in navigation traffic at the lock. This range of data should be compiled into a design matrix and processed with return periods for anticipated events at the particular structure. Return periods were previously discussed in paragraph B-3. For preliminary or feasibility design efforts, engineering judgment should be used to formulate reasonable impact angle and velocity scenarios. For some existing locks, the designer may have information available from previous model studies or lockmaster logs. Other ways to obtain data for feasibility level designs could be from using lockmaster's logs or towing industry records from similar existing facilities. This type of data should be utilized only during conceptual design and should not be incorporated as the only source of data for the final design. Limited data could result in an unsafe or uneconomical design of the navigation structure. As work progresses toward the final design, the range of values for impact angles and velocities should be defined with reasonable certainty. Measurements for these parameters can be made in the field using time-lapse video photography or in a laboratory scale model. Relative merits of each method are discussed in *c*(5) and *c*(7) below.

b. Site constraints.

(1) Approach walls are provided upstream and downstream of lock chambers. Approach walls adjacent to the dam are commonly referred to as guard walls and the walls opposite the guard walls are usually referred to as guide walls. The walls are used by approaching barge traffic as landing or holding points prior to entering the lock chambers. Barge traffic routinely impacts the walls at ranges of velocities and angles that are constrained by the geometry of the site. This is shown in Figure B-7. Approach walls are designed to accommodate a wide variety of operating conditions that range from normal river conditions to flood events. The levels of loading that the walls resist should be consistent with a probabilistic approach where loading is classified as usual, unusual, or extreme based on a given return period of the event.

(2) Generally, the upstream approach walls are designed for a higher impact load than the downstream walls as explained below. Upstream of the lock, riverflow is distributed from bank to bank. The cross-sectional area of the lock in the river will partially block bank-to-bank flow. To improve hydraulic

conditions, the upper guard wall is usually ported (a system of openings designed by hydraulic engineers) below the impact face to allow flow under the wall. Outdraft conditions or currents (see Figure B-7) toward the upstream guard wall influence both impact speed and angle in a predictable manner over the range of flow conditions.

(3) The following fundamental differences influence the design of walls impacted by upbound or downbound traffic. Downbound traffic is moving with the current whereas up bound traffic is moving against river current. Towboats usually have more control moving upstream against the current than moving downstream with the current. The disparity in load conditions for upstream and downstream walls becomes more pronounced as flood conditions are encountered.

(4) Usual impact forces are based on typical river conditions and assume a controlled landing against the wall with a typical barge configuration. The usual load reflects typical operating conditions. Unusual impact forces may occur prior to navigation shutdown prior to a flood event, when fully loaded barges attempt a lockage in fast river currents. They may also occur when approach conditions are exacerbated by outdraft currents in the upper approach. The vessel will usually be traveling at a greater velocity and may impact the approach walls at larger angles during these conditions, resulting in higher impact forces. The conditions associated with extreme impact forces are highly unpredictable and difficult to establish. Extreme events can occur when a towboat pushing a barge train loses power under normal conditions. They can also occur during a flood event when navigation has shut down and barges break away from moorings and float out of control downstream. Hydraulic modeling should be used to investigate various scenarios to gain insight and data for design.

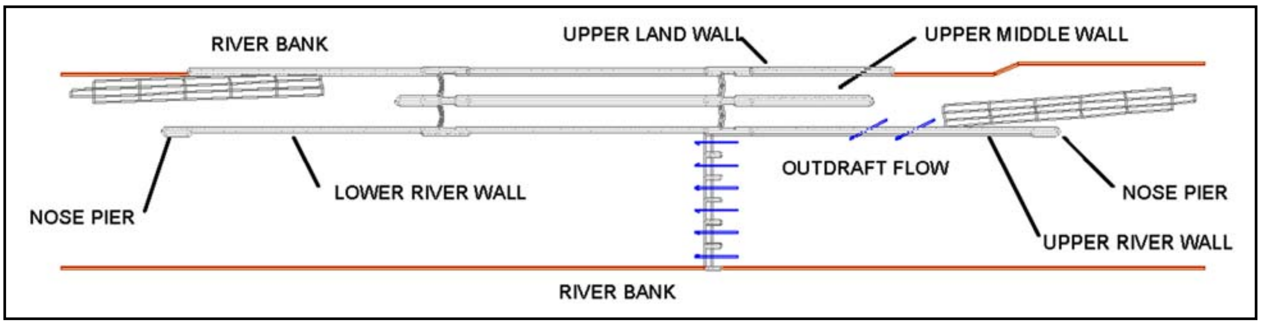

Figure B-7. Site constraints for a typical lock structure

c. Data requirements.

(1) Barge train size. The dimensions of lock chambers are typically based on the sizes of barge trains that will use the lock. The most common barge on the inland waterway is the jumbo barge, which is 11 m (35 ft) in width and 59 m (195 ft) in length. Typical configurations are generally three wide by five long (32 m (105 ft) wide by 358 m (1,175 ft) long, including 61 m (200 ft) for the towboat) or three wide by three long (32 m (105 ft) wide by 239 m (785 ft) long, including 61 m (200 ft) for the towboat). On some rivers, the standard barge is generally 8 m (27 ft) in width and 53 m (175 ft) in length. There are older barges in service that are 7 m (24 ft) wide; however, these barges are slowly being removed from service. Another type of barge is the double-hulled oil, gas, and chemical barge. These barges are typically 15 to 16 m (52 to 54 ft) in width and 61 to 91 m (200 to 300 ft) in length, and travel the river in a one-wide by two-long or a two-wide by two-long configuration, depending on the river system.

(2) Barge train mass.

(a) The mass is based on the total weight of the barge and the commodity being carried in the barge hopper. Weights for inland waterway barges are generally expressed in short tons (2,000 lb per ton). A loaded jumbo open hopper barge drafting 3 m (9 ft) typically weighs between 680 to 862 kg (1,500 to 1,900 tons). Typical weight of an empty barge is 91 to 122 kg (200 to 270 tons). The mass (kip-sec^2/ft) is determined by dividing the weight by the gravitational constant g (32.2 ft/sec^2). In addition, the mass of the towboat should also be included when calculating the mass of the barge train.

(b) The mass for a barge train can be determined from different sources nationwide depending upon the river system. For data prior to the year 2000, the Lock Performance Monitoring System (LPMS) is available for all USACE locks and dams in the United States. In the year 2000, the Lakes and Rivers Division (LRD) and Mississippi Valley Division (MVD) created their own database called OMNI for the locks within their divisional territories. The Rock Island District has been collecting and processing OMNI traffic data since 2000. The OMNI database is not currently cross-linked to the national LPMS database since they use different database schemes. The national LPMS database (excluding OMNI data) contains records from 1984 to present, and records are available from the Navigation Data Center at the Institute for Water Resources. Both LPMS and OMNI contain such information as the total weight of each barge train, type of commodity, and number of barges (loaded, unloaded). However, the weights in both LPMS and OMNI are typically rounded by lock personnel to simplify their input into the databases.

(c) If more accurate weights are desired for the barge impact analysis, data from the Waterborne Commerce (WBC) Statistics Center records could be utilized. WBC data can be obtained from the USACE Navigation Data Center at the Institute for Water Resources (IWR): http://www.iwr.usace.army.mil/ndc/index.htm. WBC data are based on the port-to-port manifest for each barge train and are available for individual years and most navigation waterways. This manifest includes the exact weight of the commodity in each barge and the weight of an empty barge. While the WBC data are more accurate than OMNI, the format for the data will require it to be processed further for use in the analysis. Table B-2 contains examples of collected data, including a comparison for various USACE locks for the year of 1999. The data show a 3 to 4 percent difference between the two databases for higher traffic locks. Locks that have smaller chambers or less traffic tend to have less than 1 percent difference in the mass.

Table B-2
Comparison of OMNI Data and WBC Data for the Year 1999

	OMNI Data			WBC Data			
	No. Loaded Barges	Weight Ktons	Average Loading tons	No. Loaded Barges	Weight Ktons	Average Loading tons	Percent Difference
Greenup	44,746	70,039	1,565	43,867	71,656	1,633	4.18%
Winfield	14,234	19,521	1,371	13,761	19,716	1,433	4.28%
L/D 1 (Green)	2,915	4,353	1,493	2,685	4,193	1,562	4.38%
Myers	44,718	71,394	1,597	44,091	72,711	1,649	3.19%
Ky Lock	26,042	40,837	1,568	25,239	40,655	1,611	2.65%
Cheatham	6,092	9,542	1,566	5,997	9,449	1,576	0.59%
Dashields	18,858	24,513	1,300	18,533	24,285	1,310	0.80%
L/D 4 (All)	1,598	1,612	1,009	1,497	1,506	1,006	-0.27%
L/D 2 (Mon)	16,311	21,124	1,295	15,981	20,762	1,299	0.31%

Note: To convert tons to kilograms, multiply by 907.1847.

(d) The distribution for the mass of a barge train can be determined using existing traffic information from OMNI or WBC. From data collected at various lock projects, the distribution for barge train mass is generally dominated by single- or double-humped (camel-backed) distributions. The reason for this is that at least one or two typical barge train configurations (e.g., 6 or 15 barges) exist in several navigation systems. This distribution should also account for any anticipated future traffic changes. Generally, the distribution for mass is the easiest one to determine.

(3) Hydrodynamic added mass.

(a) Forces due to the momentum of the water associated with the moving barge train are typically included when developing impact forces. This phenomenon is known as hydrodynamic added mass and would normally be considered in the transverse, longitudinal, and rotational directions. Equations to calculate the added mass are based on traditional ship design techniques. Generally, the added mass for barge trains has been assigned 40 percent in the longitudinal, 5 percent in the transverse, and 40 percent in the rotational directions.

(b) It is important to recognize that the effect of hydrodynamic added mass is included in the measured force data used to develop the empirical relationship discussed in paragraph B-2. Therefore, the mass term in the empirical correlation used in this ETL should include only the mass of the barge train.

(4) Drag and cushioning effects on barge trains. The drag force is the resisting force of water to the momentum of the barge train, and it can be applied as a damping coefficient or percent damping in an MDOF analysis. The drag force on a barge train is not significant in comparison to the magnitude of the impact force. Cushioning forces between the barges and walls are usually not included, but may be significant for broadside impacts. The effects of drag and cushioning forces were included in the measured force data used to develop the empirical relationship discussed in paragraph B-2. Further consideration of these forces is not necessary in the empirical model.

(5) Velocity components normal and parallel to the wall.

(a) Velocities for barge trains can be estimated using field and/or laboratory methods. Two components of barge velocity (forward V_{0x} and lateral V_{0y}) should be determined for barge impact analysis. These components are shown in Figure B-5. These components of the barge motion are combined to form components normal and parallel to the rigid wall. Typically, the normal component is important since it usually contributes to the primary force used for the wall design. The parallel component will be important to structures that use end support piers to handle the shear load and for operating conditions that cause a broadside impact of the barges against the lock wall.

(b) For flood events, the upper limit for velocities of barge trains approaching a lock can be based on the velocities of the currents, the local flow regimes, or results from navigation models. During a major flood event, navigation ceases for safety, which should be considered when selecting appropriate velocities for design. Outdraft or currents near open or ported approach walls should also be considered in selecting velocities that are used for the impact analysis. For usual events, the maximum barge train velocities can be estimated using average daily flow velocities of the currents adjusted for the ability of the operator to control the barge train. For unusual events, the maximum velocity may be estimated using daily flow velocities of the currents adjusted for local conditions, such as an outdraft, that challenge the ability of the operator to control the barge train. For extreme events, the maximum velocity may be estimated using flow velocities for river conditions approaching major flood stages that challenge the ability of the operator to control the barge train.

(c) Velocities can be determined in the laboratory using scale model hydraulic testing. These models are scaled at typically 1:120 but can range down to 1:50 if required. This laboratory method requires the construction of a scale navigation model at the U.S. Army Engineer Research and Development Center (ERDC). Figure B-8 shows a typical navigation model used for barge impact testing. An overhead recording system is used to track the barge train in XYZ space on the navigation model. The data are collected by a computerized acquisition system and then processed to determine the velocities and angles during the entire approach to the lock. When performed in conjunction with a navigation study, these types of experiments are cost-effective.

(d) After the construction of the model is complete, testing is conducted using a scale model barge and towboat. The barge trains used for the experiments can be sized to fit the current and future trends of navigation traffic. In addition, the testing can model the approach of the barge train at a variety of flow conditions. Obtaining impact data at different hydraulic conditions should be an integral part of any model test matrix. Velocities in the approaches should cover a minimum of three flow conditions where probabilities can be defined by hydraulic curves for the site. A typical range of flows should not exceed probabilities of 2, 50, and 99 percent. The hydraulic engineer on the design team should furnish these values. A testing matrix for the project should also be developed for each flow condition that requires testing. To provide a statistically significant sample size, a minimum of 30 experiments should be conducted for each flow condition. Also, using two or more model barge train operators for the range of experiments would yield better information on the range of impact velocities and angles.

(e) Caution should be exercised when interpreting the raw data from the experiments due to the scale model effects of water near the structure. This cushioning effect of the barge train as it approaches the lock wall creates a slowing in the velocity prior to impact into the wall. A solution to offset this effect would be to use a time averaging scheme for the values of velocity 3 m (10 ft) prior to and 3 m (10 ft) past (in scale) the point of impact.

(f) Another method to collect data on velocities is using time-lapse videotape or Time-Lapse Data Acquisition (TLDAQ) system. These systems were first developed and utilized to collect velocity and impact data for concrete deterioration models for the Upper Mississippi River – Illinois Waterway Navigation Study in Patev, Mlakar, and Bryant (2000). Additional research was conducted in the TLDAQ systems to develop a PC-based computer data collection system that could incorporate needed measurements (i.e., wind, flows, etc.) in the field. These systems were recently developed under the Innovations for Navigation Projects R&D Program Barge Impact Work Unit and have been used in a wide variety of navigation projects including, most recently, Kentucky Lock and J. T. Myers Lock and Dam. Figure B-9 shows the installation of this TLDAQ equipment at Kentucky Lock. This type of data collection system is a very useful tool both to document the existing approach and examine any potential future needs or design changes that might be required. While this methodology is most useful if the navigation conditions are not drastically changed, it can still be applied to examine approach conditions of barge trains subjected to the effects of hazardous outdrafts and existing current conditions at the site.

(g) TLDAQ systems require the installation of a video camera and computer acquisition system or time-lapse VHS recorder. The camera is mounted to either a light standard on the existing approach wall or lock chamber or a bridge over the approach. The recording device is placed either in a weatherproof case or within a secure building. These systems are set up to record the motion of the barge trains as they navigate the approach to the lock. These systems capture a wide variety of data and information that can be processed later from the recorded media using different interpretational techniques to get velocities and angles.

(h) Table B-3 shows typical ranges of impact velocities for approach conditions to navigation lock walls that are appropriate for preliminary analyses only. Accurate determination of velocities for final design should be made using one of the methods presented above that may be appropriate.

Figure B-8. Scale navigation model of Greenup L&D used for impact testing (Note: Scale model barge with tracking lights approaching the upper guard wall in top of photograph)

Figure B-9. Demonstration of time-lapse equipment installed at Kentucky Lock (computer acquisition system on left and time-lapse camera on right)

Table B-3
Typical Ranges for Impact Velocities for Preliminary Analyses

Load Condition	Forward Velocity V_{0x}, ft/sec	Lateral Velocity V_{0y}, ft/sec
Usual	0.5 – 2.0	0.01 – 0.1
Unusual	3.0 – 4.0	0.4 - 0.5
Extreme	4.0 – 6.0	<1.0

Note: To convert ft/sec to m/sec, multiply by 0.3048.

(6) Angular velocity. Barges tend to rotate about their center of mass and not typically at the geometric center of the barge train. If this rotation is significant, it can cause either an increase or decrease in the velocity components for the impact. For preliminary design, the angular velocities can be ignored in the impact analysis. If there is concern about outdraft currents at a navigation site, rotation of the barge train should be investigated using a hydraulic scale model. Note that during the experiments used to establish the empirical model, as described in Appendix F, care was taken to minimize rotation of the barge train before and after impact.

(7) Angle of impact.

(a) The angle of impact for a barge train governs the magnitude of the velocity components to the wall. This parameter is very important to define as accurately as possible. The impact angle typically may be assumed to be a function of site geometry, functional layout, and flow conditions. The angle is also heavily influenced by the towboat operator’s ability to maneuver into the lock approach under adverse operating conditions such as high flows or stormy weather. The impact angle can be captured using either of the methods (scale models or time-lapse) as discussed. Scale model experiments may lead to less accurate angles unless special provisions are made to account for the effects of water cushioning. Caution should be exercised when using time-lapse video to measure the impact angle. A range of angles should be calibrated in the field of view and applied to the results to avoid inaccuracies that may be in the range of 10 to 20 percent.

(b) For preliminary analyses, Table B-4 shows typical values for impact angles for approach conditions to navigation lock walls. Accurate determination of impact angles for final design should be made using one of the methods presented above.

Table B-4
Typical Ranges for Impact Angles Used in Preliminary Analyses

Load Condition	Approach Angle, deg
Usual	5 - 10
Unusual	10 - 20
Extreme	20 - 35

(c) The distributions for impact angle and velocity can be based on data from either geometric constraint, scale model testing, or time-lapse video. From the results of previous PBIA, the distribution for velocities and angles are lognormally distributed. This is a reasonable observation since most of the angles and velocities that occur in the field are generally skewed to the left of the average value. These distributions may be truncated depending upon certain physical limitations that exist at a navigation site.

(d) The trend from previous PBIA, as shown in Appendix C, indicates that the average range for the mean normal impact velocity falls within the 0.3- to 0.5-m/sec (0.75- to 1.5-ft/sec) range and average angles tend to be around 4 to 8 degrees. This will, however, vary greatly depending upon the site-specific conditions that are being analyzed in the PBIA. Another item to include in the PBIA is the correlation between the mass, velocity, and angle. From previous PBIA, a direct correlation between mass, velocity and angle has been observed. For example, a large barge train (15 barges) will generally approach a lock wall with a slower velocity than a smaller barge train (2 barges). These correlations should be investigated and accounted for in any PBIA.

B-5. Barge Impact Analysis for Rigid Walls

a. Barge impact is an important load case in defining the wall dimensions in either preliminary or advanced designs. The method presented in this ETL is based on the direct results from the full-scale experiments as discussed in Appendix F. The empirical equation developed to estimate the impact load normal to the structure is implemented as part of this ETL for rigid walls.

b. There are other considerations that can also be factored into the design of rigid walls for barge impact:

(1) For preliminary designs of lower approach walls, the loads can be presumed to be one-half those loads for the upper approach walls. During advanced design phases, additional scale modeling or time-lapse video should be utilized to confirm that this presumption is correct.

(2) Since most barge impact analyses focus on the loads for the approach walls, a presumed value of 445-667 kN (100-150 kips) may be applied as the minimum impact forces for preliminary design on chamber walls. Additional hydraulic modeling should be considered for small barge trains impacting chamber walls at greater angles.

(3) The forces from head-on impacts into bull noses, protection cells, and lock walls are a difficult problem to solve. This is due primarily to the complexity of the interactions between the breaking of the lashings and the crushing of the rake of the barge during the impact. This interaction can be modeled using either empirical equations from mechanical models or complex finite element modeling of the barge system. Based on current research efforts, other design methods that are available, and the use of expert judgment within the USACE, a value of 8,896 kN (2,000 kips) is recommended to be used for the preliminary design of rigid walls subjected to head-on collisions. For final design values for head-on impacts, consultation with CE-CW is recommended until additional research is conducted on this issue and additional guidance will be provided.

(4) The design of a navigation lock should use different values of impact forces and return periods for the structural analysis of each wall section. Figure B-10 shows an example layout of a lock and the location for the values of impact forces determined using the PBIA procedures defined previously. Table B-5 shows an example of the impact location and loads to be used for preliminary design of a lock structure.

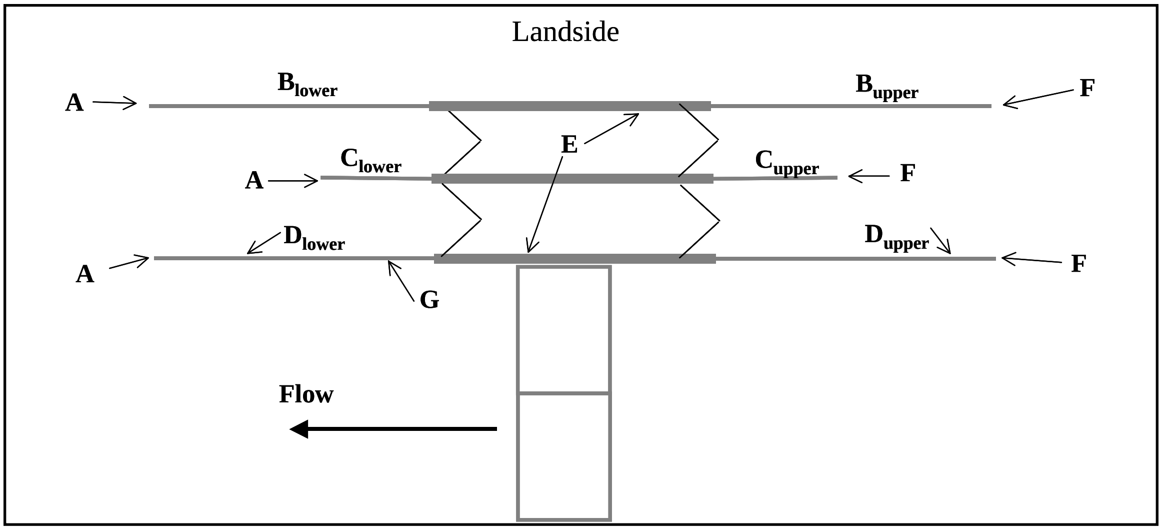

Figure B-10. Examples of impact loads on lock structures (see Table B-5 for explanation of symbols)

Table B-5
Example of Preliminary 9-Barge Design Impact Forces and Locations

Symbol (Figure B-10)	Location	Event	Impact Load, kips
A	Lower protection cell/bullnose	Extreme	1,000
B_{lower}	Lower land wall	Usual	150
		Unusual	250
		Extreme	350
B_{upper}	Upper land wall	Usual	300
		Unusual	500
		Extreme	700
C_{lower}	Lower middle wall	Usual	100
		Unusual	150
		Extreme	250
C_{upper}	Upper middle wall	Usual	200
		Unusual	300
		Extreme	500
D_{lower}	Lower river wall	Usual	200
		Unusual	300
		Extreme	400
D_{upper}	Upper river wall	Usual	400
		Unusual	600
		Extreme	800
E	Chamber walls	Usual	100
		Unusual	125
		Extreme	150
F	Upper protection cell/bullnose	Extreme	2,000
G	Maintenance Impacts	Loads presented are for commercial barges. These design forces on this portion of the wall should use values based on anticipated operation and maintenance practice.	

[1] To convert kips to kilonewtons, multiply by 4.448.

Appendix C
Data from Previous Studies

C-1. Introduction

This appendix documents several inland navigation studies that have performed analyses to determine the distribution of velocities and impact angles for tows in the design of their approach walls. The purpose of this appendix is to provide some basic design information on distributions for velocity and angles so that designers can gain an understanding of the scope of what needs to be developed for their own navigation study efforts. The data summaries are presented for the typical design parameters (velocity, angle, and mass) used in design of approach walls at Olmsted Lock and Dam (L&D) (Ohio River), Winfield L&D (Kanawha River), Kentucky L&D (Tennessee River), Marmet L&D (Kanawha River), London L&D (Kanawha River), and Greenup L&D (Ohio River). A brief description of the approach walls that were designed, plans, and hydraulic flow vectors from the navigation model, if available, are presented for each project. However, many of the distributions presented in these examples are documented using a Beta Subjective distribution. These distributions have been converted to a lognormal distribution with matching statistical parameters (i.e., mean, standard deviation and percentiles) since the Beta Subjective distribution is not always recommended for probabilistic analysis. Correlation coefficients for the velocity, angle, and mass are shown for the Marmet L&D project.

C-2. Project Examples

a. Olmsted Approach Walls, Ohio River, Olmsted, Illinois (Design Memorandum for Olmsted Lock and Dam, Louisville District, 1999).

(1) The Louisville District began construction of the first phase of the Olmsted Locks and Dam project in 1993. The Olmsted Locks project began in 1996 and included the construction of two 366-m- (1,200-ft-) long lock chambers. Toward the end of the construction contract for completion of the locks, the contract to construct the approach walls began in 1999. The Olmsted approach walls project included four floating guard walls and one fixed guide wall; the four guard walls are aligned between the dam and the lock approaches. Figure C-1 shows the layout of the approach walls at Olmsted L&D. The Olmsted Locks are aligned close to the Illinois shore; thus the approach angles for barge trains entering the locks are not expected to be large. The walls were designed for the Louisville District following the method described in ETL 1110-2-338. At the time of the design, there was not yet a set of locks at Olmsted at which the behavior of arriving barge trains could be observed. Therefore, the design of the walls included data from model testing on a 1:120-scale model at ERDC and the use of time-lapse videotape of the approaches at both Smithland Locks and Uniontown (currently called J. T. Myers) Locks since the characteristics of the barge traffic and the flow of the Ohio River at these projects were judged to be similar to Olmsted.

(2) The results from the scale model were used primarily to determine the barge impact parameters for the design of the approach walls. The videotape data from Smithland and J. T. Myers were used to validate the approach and landing of tows and the currents in the scale models, and engineering judgment was used to combine the results of these discrete studies in development of the design parameters at Olmsted. Figure C-2 shows the velocities and flow vectors from the ERDC scale model, and Figure C-3 shows the time trace of the tow as it makes its approach to the locks under controlled landing scenario. From the processing of the scale model experiments, the probability distribution for the impact angle is shown in Figure C-4, the probability distribution for the longitudinal velocity V_{0x} is shown in Figure C-5, and probability distribution for lateral velocity V_{0y} is in Figure C-6. The probability distribution for mass of the tows was taken from downbound traffic data at Lock 52, which is 40 km (25 miles) downstream.

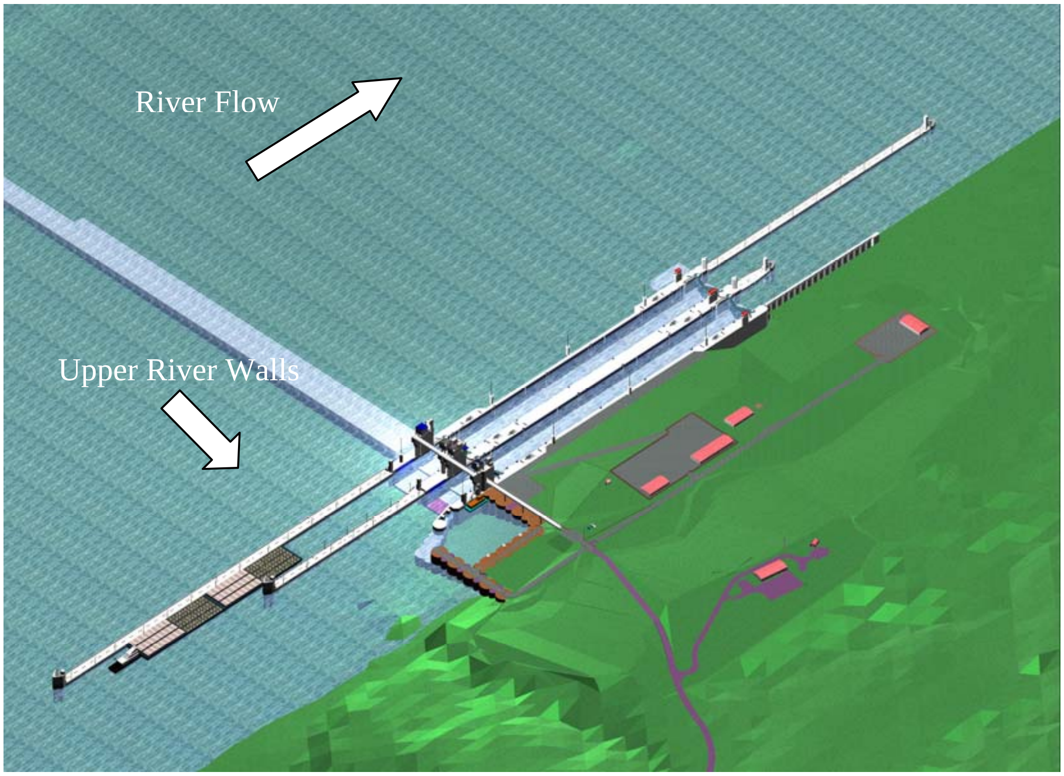

Figure C-1. Olmsted locks and approach walls

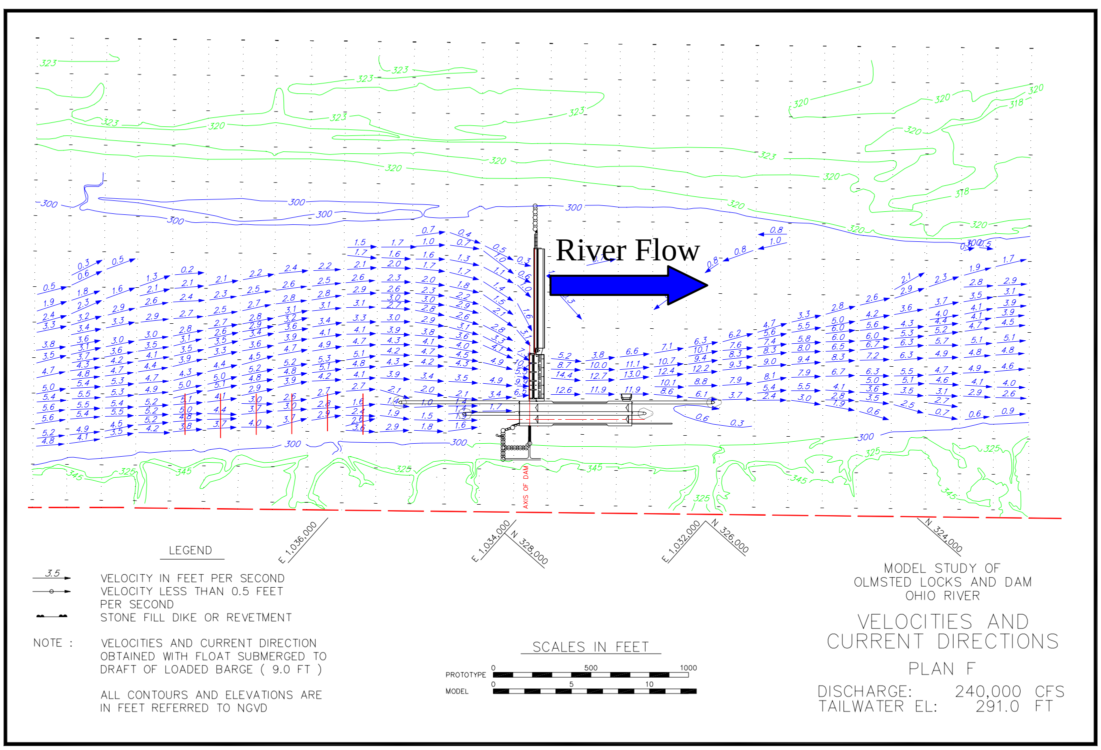

Figure C-2. Hydraulic flow results from navigation model for Olmsted L&D

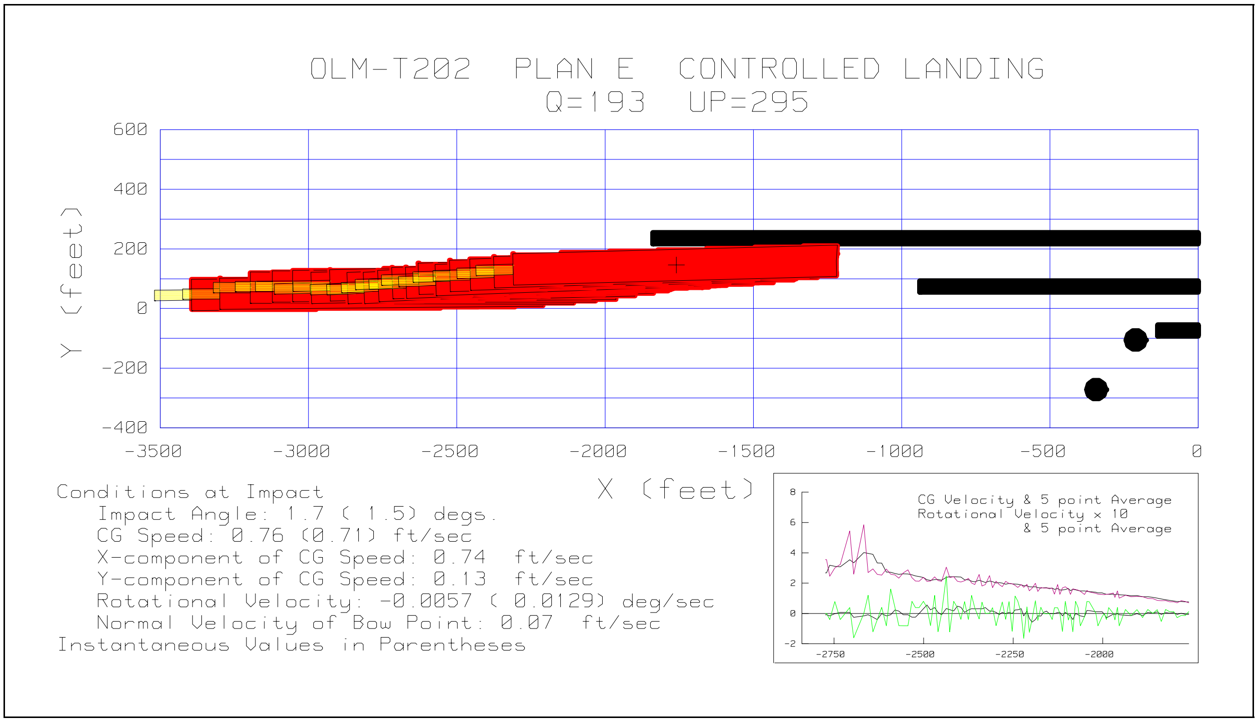

Figure C-3. Typical trace of experimental barge impacts at Olmsted upper river approach wall from the ERDC 1:120 navigation model

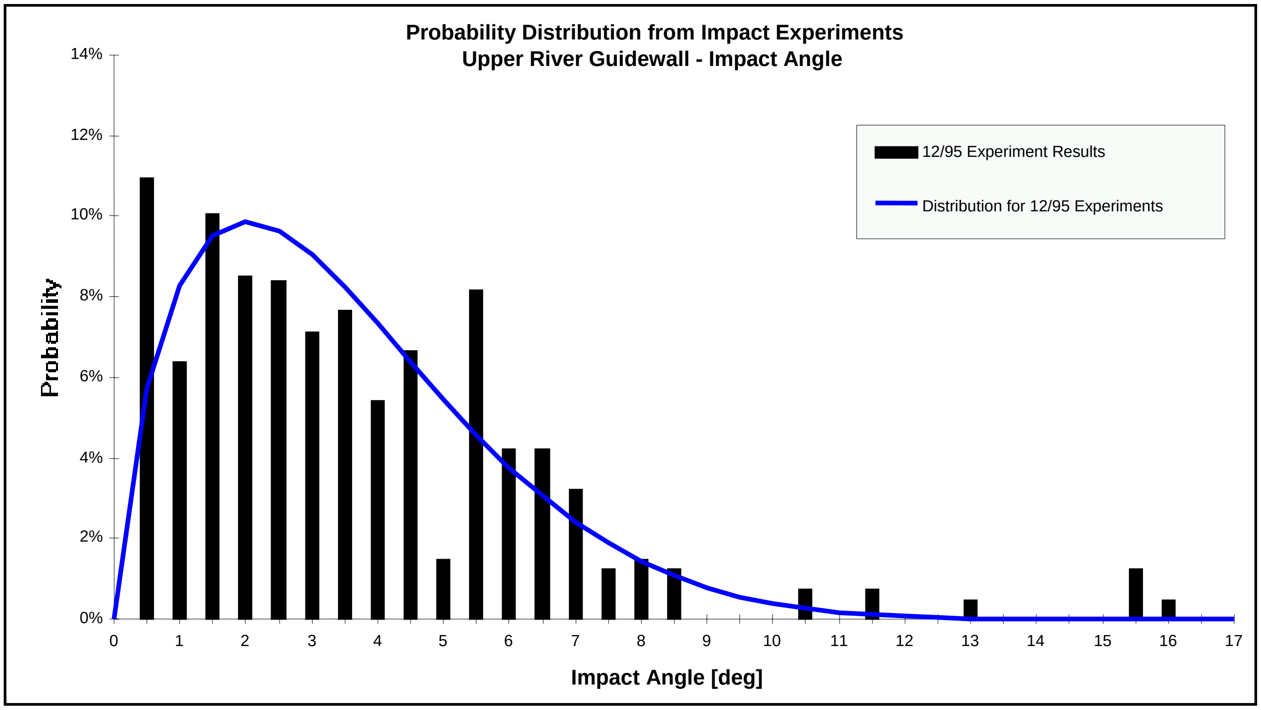

Figure C-4. Probability distribution of impact angle for Olmsted upper river approach wall

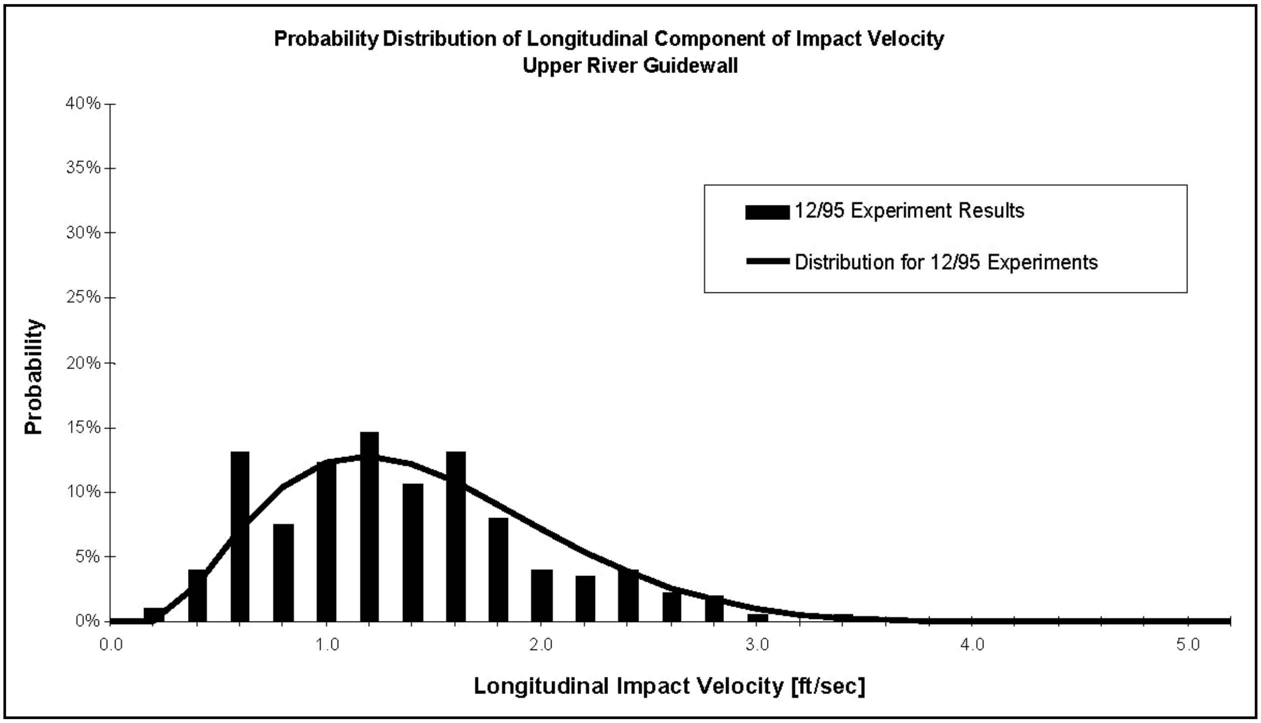

Figure C-5. Probability distribution of longitudinal impact velocity V_{0x} for Olmsted upper river approach wall

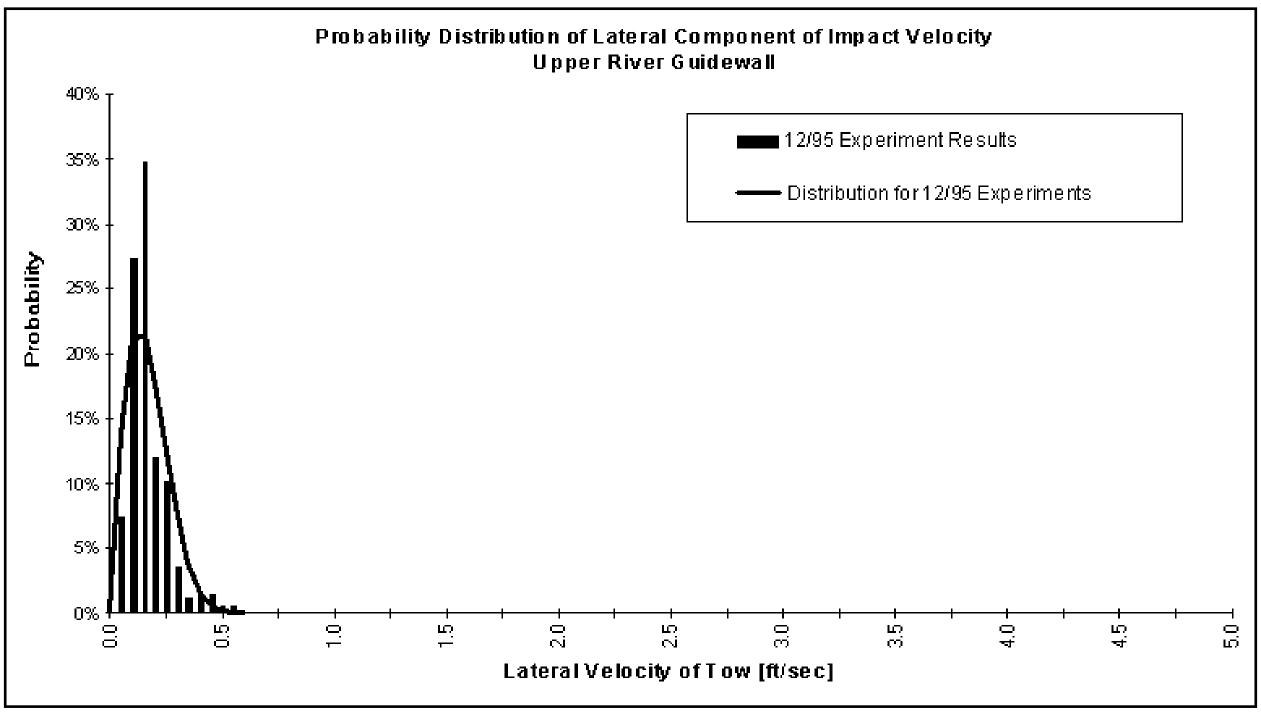

Figure C-6. Probability distributions of lateral velocity V_{0y} for Olmsted upper river approach wall

This distribution for mass is shown in Figure C-7. A summary of the statistical parameters used for the barge impact design of the upper river guide wall is shown in Table C-1.

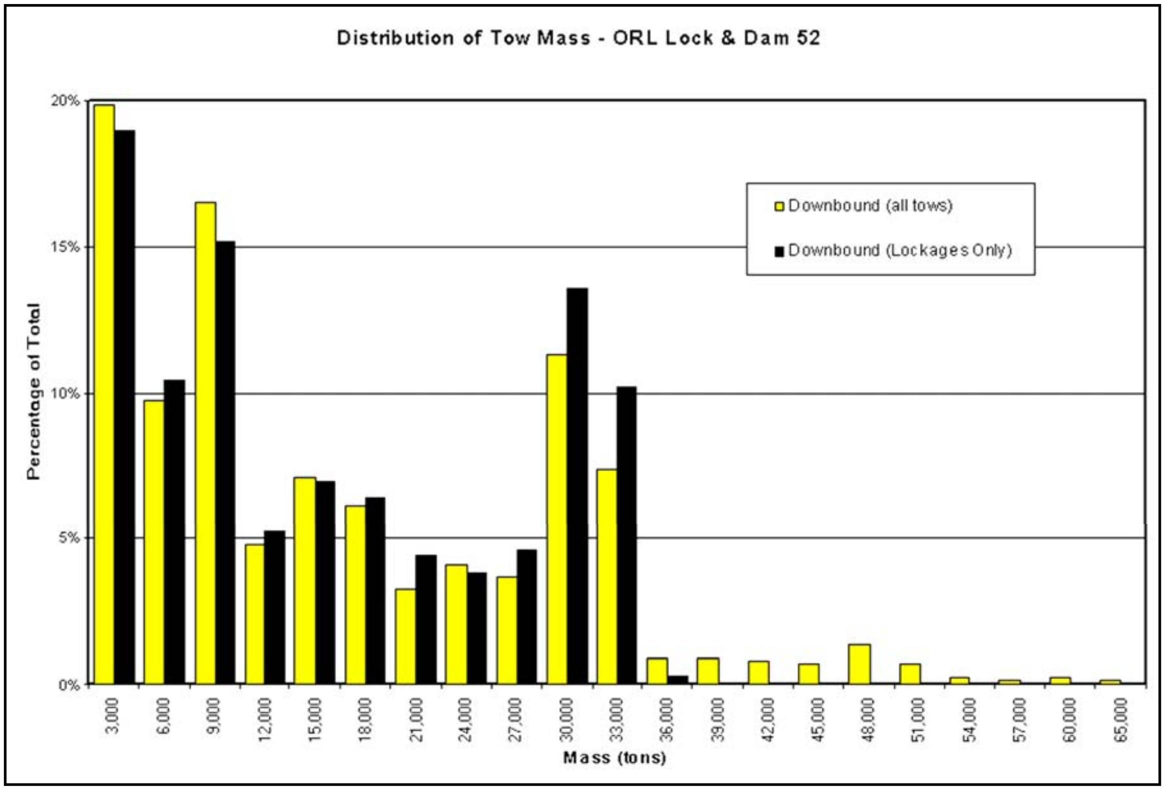

Figure C-7. Probability distribution of tow mass for Olmsted upper river approach wall (data taken from Lock 52, located 40 km (25 miles) upstream)

Table C-1
Lognormal Distribution Parameters for Impact Variables, Olmsted Upper River Wall Approach Wall

Design Structure	Variable	Mean	Standard Deviation	Minimum	Maximum
Upper river guide wall	θ, deg	3.3	2.2	0	17
	V_{0x}, ft/sec	1.27	0.62	0	4.8
	V_{0y}, ft/sec	0.07	0.092	0	1

b. Winfield Upper Approach Guard Wall, Kanawha River, Winfield, West Virginia (Design Memorandum, Winfield Lock and Dam, Huntington District, 1995). The Huntington District completed construction of a new main lock chamber and upper approach guard wall at Winfield Locks in 1997. The new main lock is 34 m (110 ft) wide by 244 m (800 ft) long. During the construction contract for the new lock, the contractor prepared a Value Engineering proposal to reduce the number of sheet-pile cells for the upper approach wall. This made the precast beams that spanned between sheet-pile cells approximately three times longer than the original contract plans had designed and new barge impact analysis for the walls was required. The barge impact design of the approach walls followed the method described in ETL 1110-2-338. The Winfield site is located on the inside of a tight bend in the Kanawha River; thus the approach angles for the upper guide wall can be expected to have a fairly wide variation. The approach for the new lock at Winfield is shown in Figure C-8. To account for this fact, the 1:120-scale model included approximately 250 simulated barge impact events for both controlled experiments that used three different operators and uncontrolled or loss of power events. For the design of the approach wall, the impact angle and forward velocity (i.e., composed of the longitudinal, V_{0x}, and transverse, V_{0y}, velocity components) data from the ERDC scale navigation model were utilized. The distributions for velocity and angle are shown in Figures C-9 and C-10, respectively. The data for the tow mass distribution as shown in Figure C-11 were obtained from the OMNI database by Huntington's Navigation Planning Center. Table C-2 shows the statistical parameters from the scale model experiments used in the design of the approach walls.

c. Kentucky Lock Addition Upper Approach Walls, Tennessee River, Grand Rivers, Kentucky (Design Memorandum, Kentucky Lock Addition, Nashville District, 1999).

(1) Nashville District started the design for this navigation project to increase the capacity for Kentucky Locks in the 1990's. The Kentucky Lock Addition consists of a new 34- by 366-m (110- by 1,200-ft) lock landward of the existing 34- by 183-m (110- by 600-ft) lock. The upper land approach wall consists of a 396-m- (1,300-ft-) long wall that is designed as a 13-m- (42-ft-) wide floating guide structure. The upper middle approach wall is similar in construction and function except that it is an 84-m- (277-ft-) long, 14-m- (46-ft-) wide wall with a 12-degree bend toward the river near the middle of the wall. This allows the floating wall to align with the landward wall of the existing lock and to guide barge traffic into the new lock. The upper approach for this project is within Kentucky Lake, which is very wide near the locks and has minimal effects on tows from either currents or outdrafts. Figure C-12 shows the layout for the upper middle approach wall.

Figure C-8. Upper approach guard wall at Winfield L&D

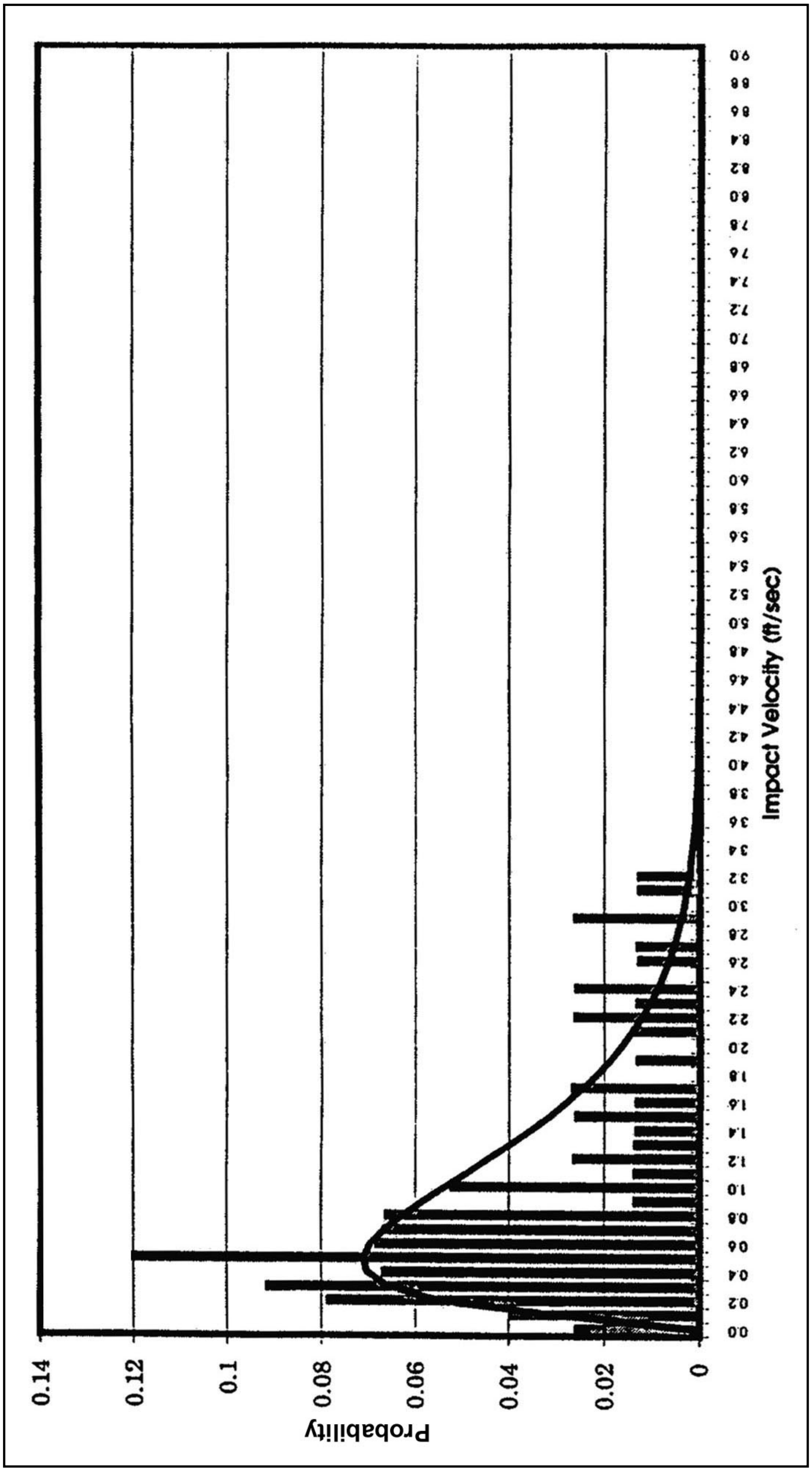

Figure C-9. Weighted histogram and fitted probability distribution function for forward velocity at Winfield upper approach guard wall

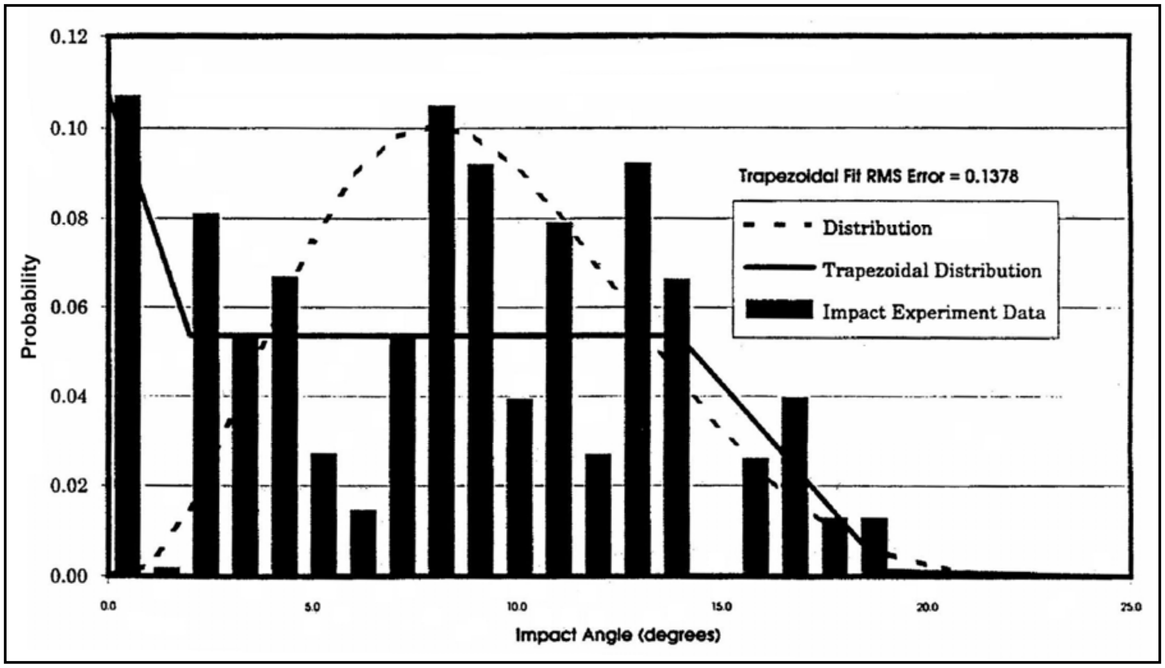

Figure C-10. Histogram and probability distribution function for impact angle at Winfield upper approach guard wall

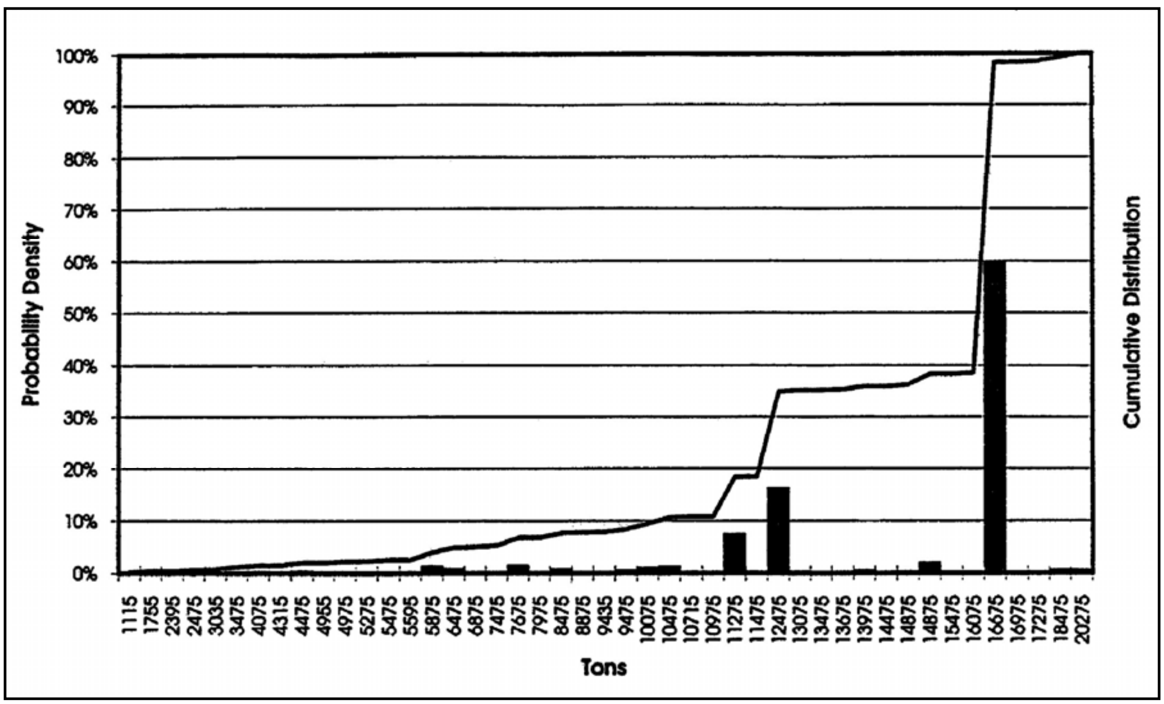

Figure C-11. Histogram and cumulative probability distribution of tow mass for Winfield upper approach guard wall

Table C-2
Lognormal Distribution Parameters for Impact Variables at Winfield Upper Approach Guard Wall

Design Structure	Variable	Mean	Standard Deviation	Minimum	Maximum
Upper approach guard wall	θ, deg	9.3	3.75	0	30
	V, ft/sec	1.08	0.7	0	10

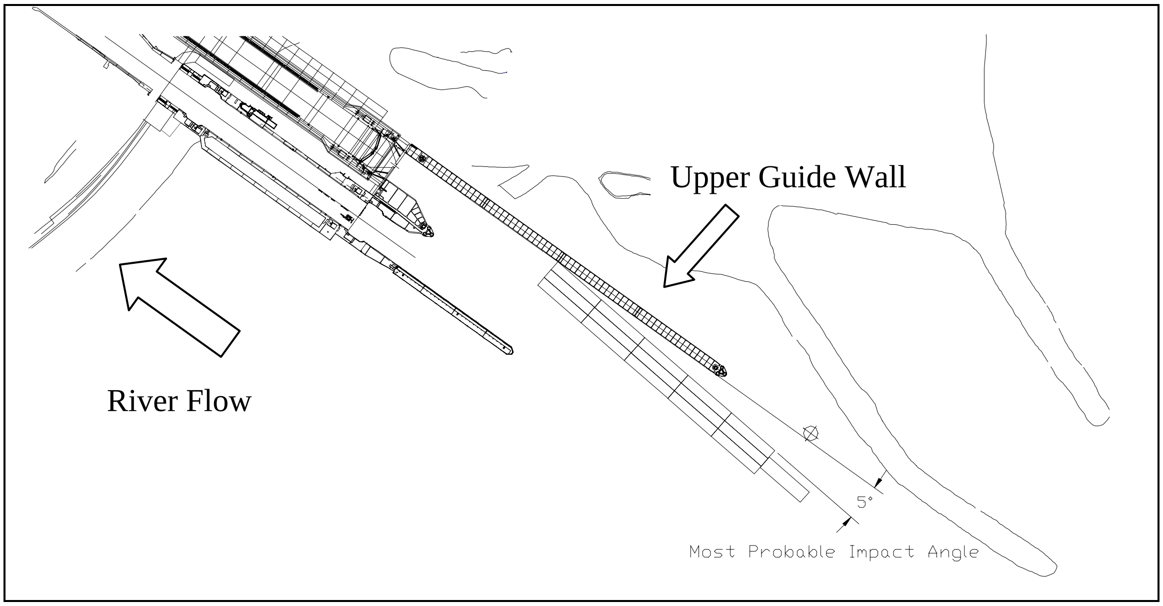

Figure C-12. Upper landside guide wall at Kentucky Locks

(2) Therefore from this design it would be anticipated that the approach angle can be expected to have a wider degree of variation than was estimated in either the Olmsted or Winfield examples above but the approach velocities can be expected to be lower. A 1:120-scale navigation model was constructed at ERDC, but no impact experiments of the upper approach walls were conducted as part of the modeling. Instead the final design incorporated the use of data from the Olmsted approach walls design since both designs incorporated floating guide walls. The experiment data from Olmsted was then adjusted based on the opinions from tow captains that utilize the locks as well as engineering judgment from District hydraulic and structural engineers. The distributions for impact and forward velocity of the barge are shown in Figures C-13 and C-14, respectively. The distribution for tow weight was taken from the OMNI database and is shown in Figure C-15. Table C-3 shows the statistical parameters used for the design of the upper guide wall.

d. Marmet Upstream Guide Wall, Kanawha River, Marmet, West Virginia (Patev 2000 and Design Memorandum, Marmet Upstream Guide Wall, Huntington District, 1999).

(1) The Marmet upstream guide wall structure consists of 14 concrete drilled piers spaced at 23 m (105 ft) center to center and a sheet-pile nose cell, which support 15 precast concrete beams. Figure C-16 shows the layout for the upper approach walls at Marmet. Each pier is constructed of two 2-m- (6-ft-) diameter drilled shafts with cast-in-place cap beams to support the precast wall beams as shown in Figure C-17. A thrust block is provided at the cap beam to transfer barge impact from the beam into the shafts and nose cell. The hollow, rectangular beams have an outside dimension of 3 m by 3 m (10 ft by 10 ft), and the weight of each of the precast beams is approximately 450,000 kg (495 tons).

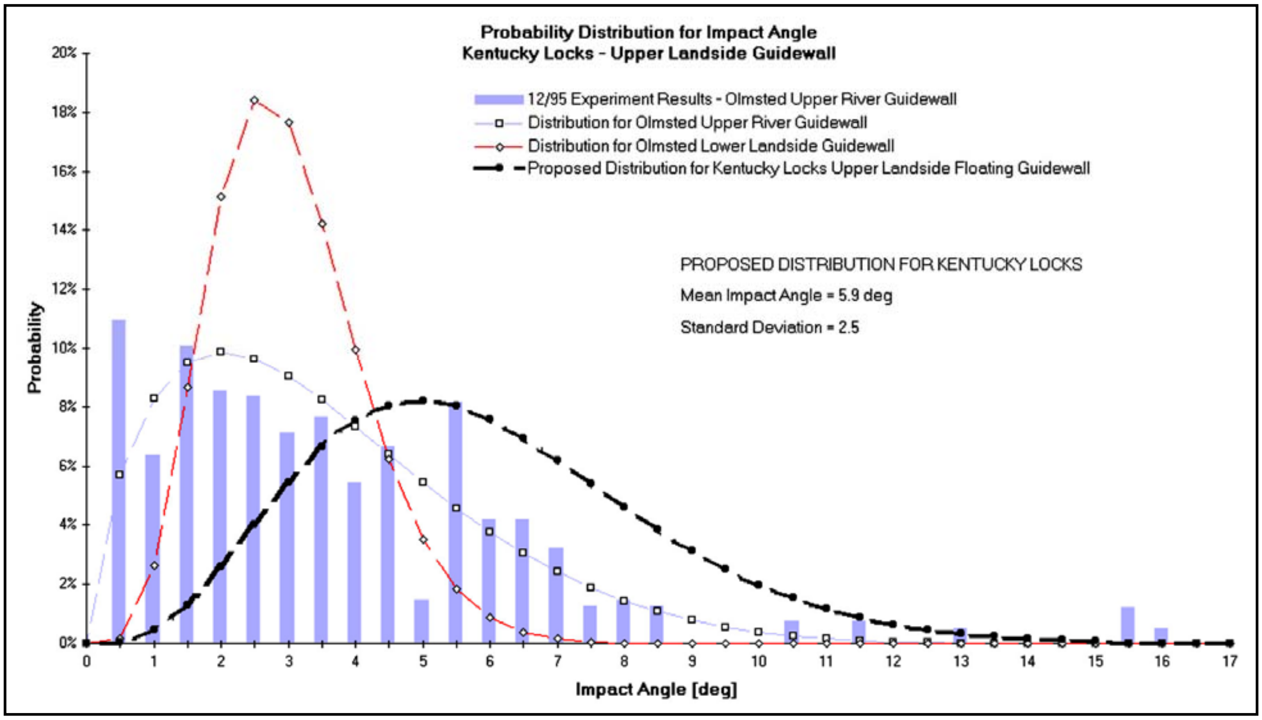

Figure C-13. Probability distribution function for impact angle at Kentucky Locks upper landside guide wall

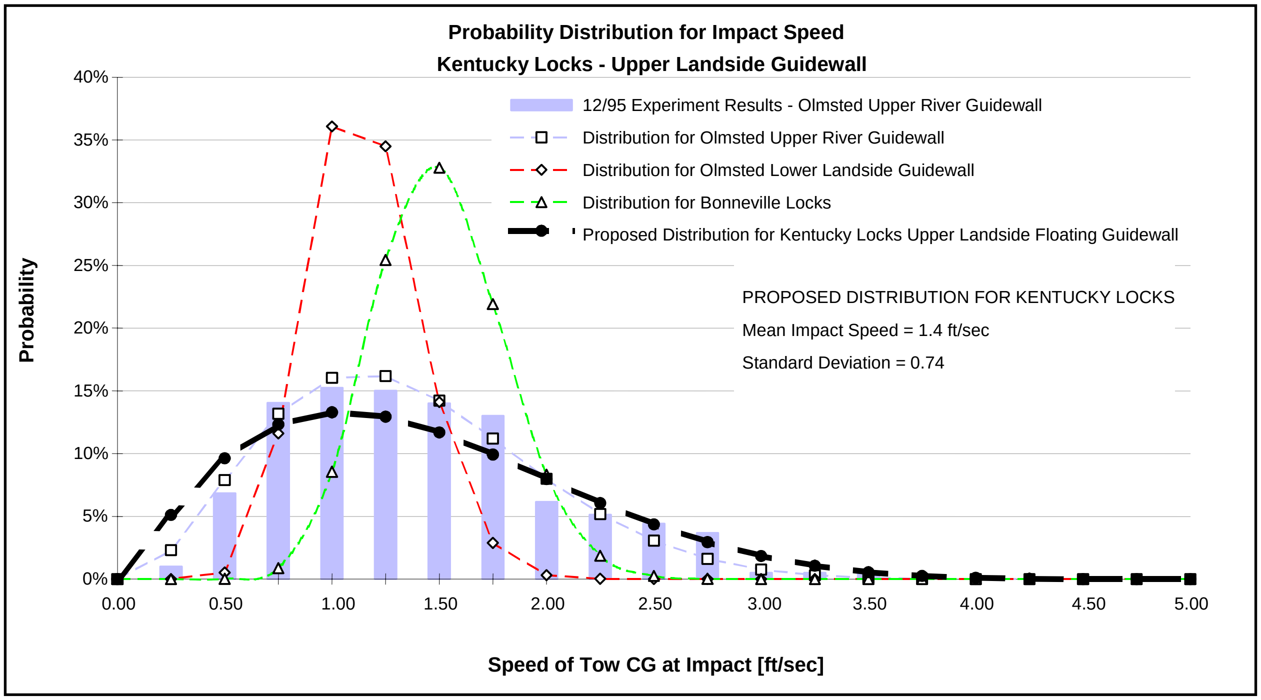

Figure C-14. Probability distribution function for forward impact velocity at Kentucky Locks upper landside guide wall

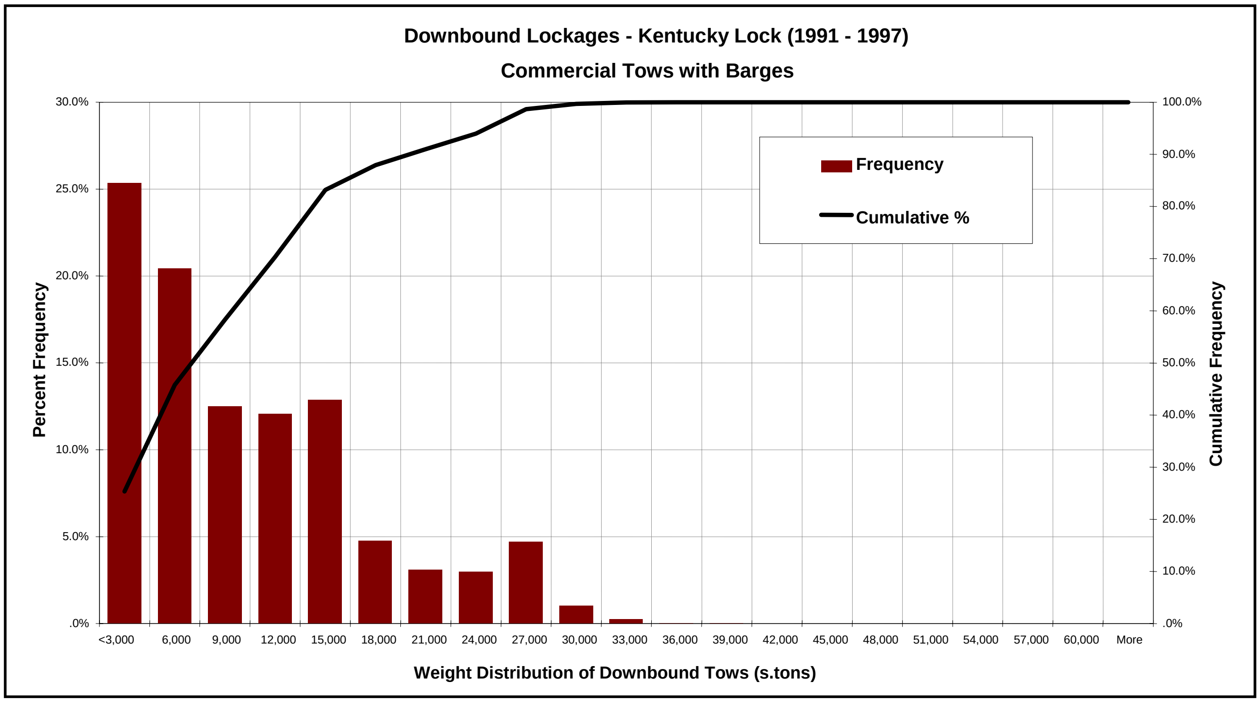

Figure C-15. Histogram of cumulative probability distribution of downbound lockages at Kentucky Locks upper landside guide wall

Table C-3
Lognormal Distribution Parameters for Impact Variables at Kentucky L&D Upper Approach Guide Wall

Design Structure	Variable	Mean	Standard Deviation	Minimum	Maximum
Upper landside guide wall	θ, deg	6.15	2.5	0	27
	V, ft/sec	1.4	0.7	0	5

(2) Scale model experiments at 1:120 were performed at ERDC to determine the approach velocities and angles of impact for both a nine-barge jumbo tow and an existing design five-barge tow. These experiments were laid out for various flow conditions to cover a range of hydraulic conditions as well as for the loss of power condition of a nine-barge tow. The flow regime for the scale model is shown in Figure C-18.

(3) Overall, five scale model testing sequences were recommended and are summarized in Table C-4. These testing sequences assisted in defining the annual probability distributions for a wide range of flows and events. An example of the statistical parameters for a 708-cu-m/sec (25,000-cu-ft/sec) flow using five standard barges is shown in Table C-5. The velocities results for these experiments were determined as both normal V_n and tangential V_t velocities to the wall and are not in barge coordinates. The correlation coefficients of the random variables from the testing data for this event are shown in Table C-6. For information on the distributions for the other testing sequences, correlation coefficients, or raw experiment data, additional details can be found in Patev (2000).

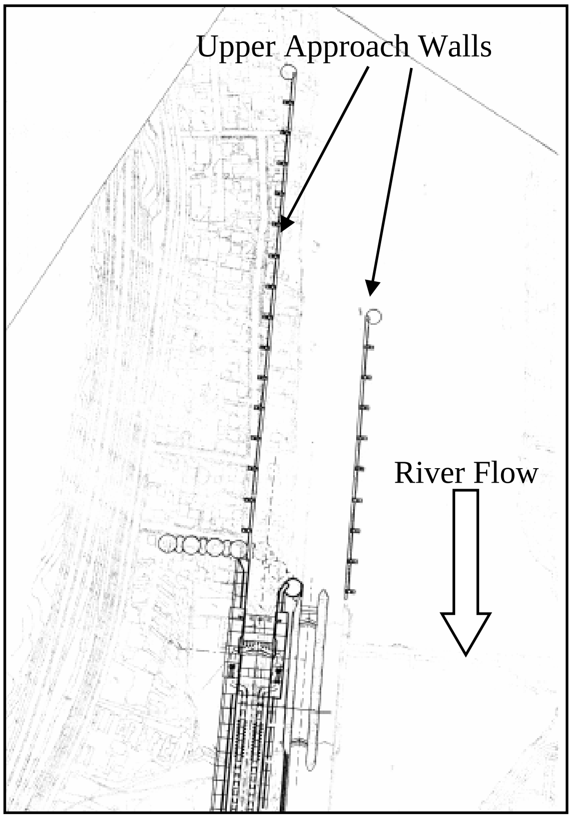

Figure C-16. Layout of upper approach walls at Marmet L&D (from Patev 2000)

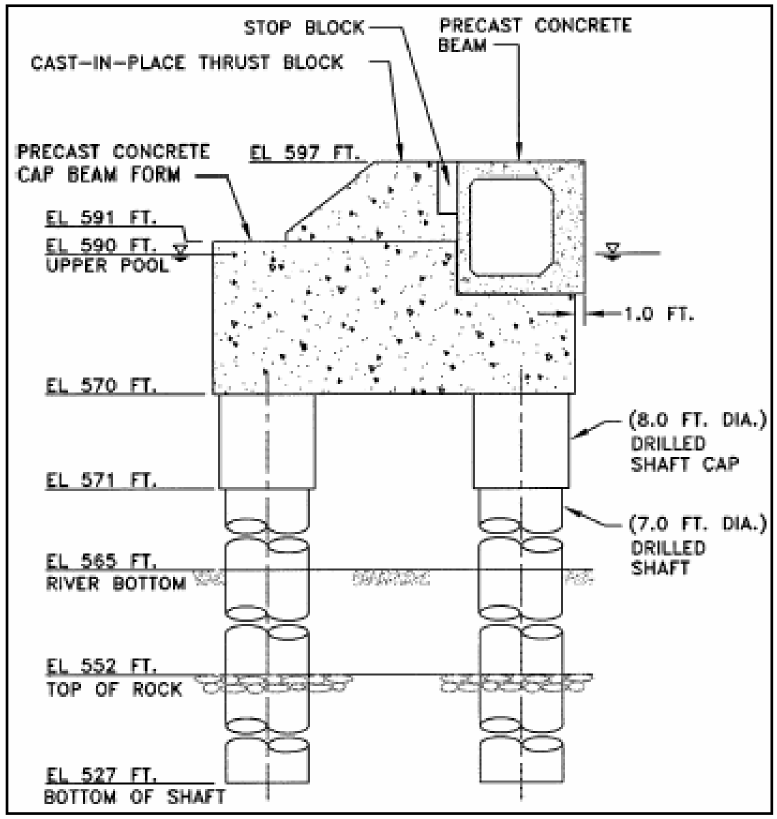

Figure C-17. Concept design of approach walls at Marmet L&D (from Patev 2000)

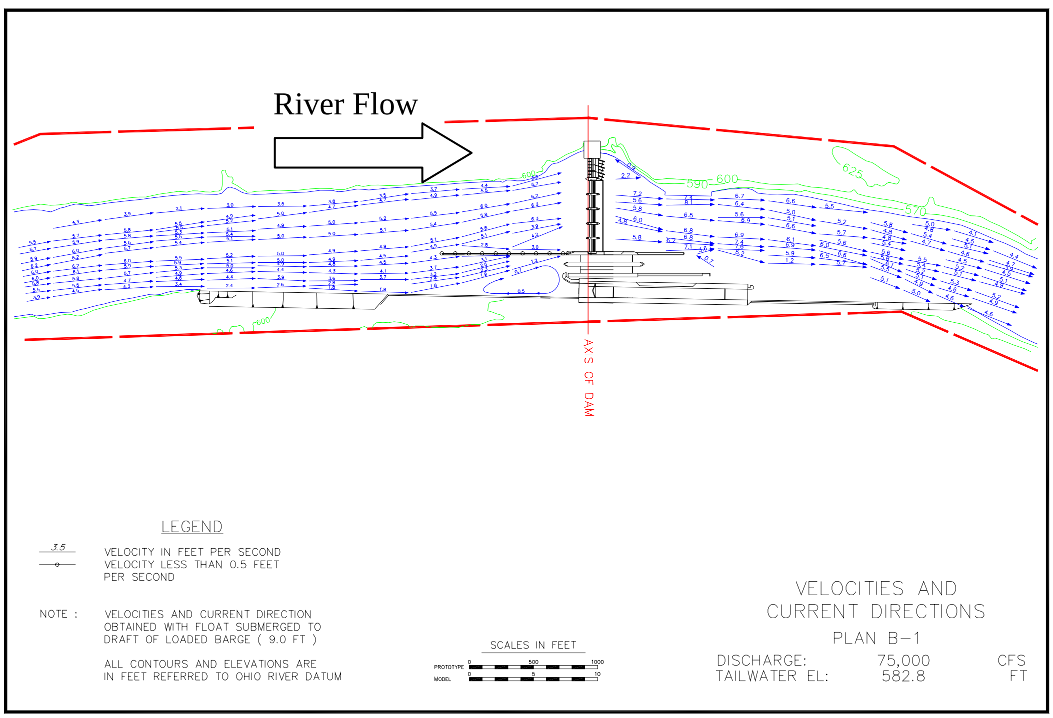

Figure C-18. Flow vectors from navigation model for Marmet L&D

Table C-4
Summary of Model Experiments for Marmet Lock and Dam (Patev 2000)

Flow Conditions, cu m/sec (cu ft/sec)	Number of Model Runs	Number of Barges	Controlled	Loss of Power	Walls Affected
708 (25,000)	25	9 (jumbos)	Yes	No	Guide wall
708 (25,000)	25	5 (standards)	Yes	No	Guard wall
1,416 (50,000)	25	9 (jumbos)	No	Yes	Guard wall/ Guide wall
3,002 (106,000)	25	9 (jumbos)	Yes	No	Guide wall
3,540 (125,000)	25	9 (jumbos)	No	Yes	Guard wall

Table C-5
Example Lognormal Distribution Parameters for Impact Variables at Marmet L&D Upper Guide Wall (Patev 2000)

Design Structure	Variable	Mean	Standard Deviation	Minimum	Maximum
Upper guide wall (708 cu m/sec (25,000 cu ft/sec) 5-barge)	V_t , ft/sec	0.94	0.4	0	5
	V_n, ft/sec	0.13	0.065	0	1
	θ, deg	6.92	1.47	0	20

Table C-6
Example Correlation Coefficient Matrix of Distribution Parameters at Marmet L&D Upper Guide Wall (Patev 2000)

Design Structure	Variable	V_t , ft/sec	V_n , ft/sec	θ, deg
Upper guide wall (708 cu m/sec (25,000 cu ft/sec) 5-barge)	V_t , ft/sec	-	0.6	0.08
	V_n, ft/sec	0.6	-	0.68
	θ, deg	0.08	0.68	-

Note: Correlation values ranges from –1 (negative) to 1 (positive).

e. London Locks Upstream Guard Wall on the Kanawha River, West Virginia (Design Memorandum, London Locks Upstream Guard Wall, Huntington District, 1999).

(1) The London Locks and Dam upstream guard wall is on the Kanawha River at London, West Virginia. The structure consists of five concrete-filled sheet-pile cells spaced at 32 m (105-ft) center to center and a concrete-filled sheet-pile nose cell, which support five precast concrete beams. Each sheet-pile cell is constructed with a thrust block to transfer the barge impact from the beam into the cell. The hollow, rectangular precast wall beams are each 32 m (105 ft) long, and have an outside dimension of 3 m by 2 m (10 ft by 8 ft) high. The weight of each of the precast beams is approximately 308,443 kg (340 tons).

(2) A 1:120-scale navigation model was developed for the London Locks project at ERDC. The flow vectors from the scale model are shown in Figure C-19. A limited number of scale model experiments under controlled events were performed to assist with determining the distributions for approach angles or forward velocities to be used in the impact design. These distributions for forward velocity and impact angle from the model testing are shown in Figures C-20 and C-21, respectively. Table C-7 shows the statistical parameters used in the design of the upper river guide wall.

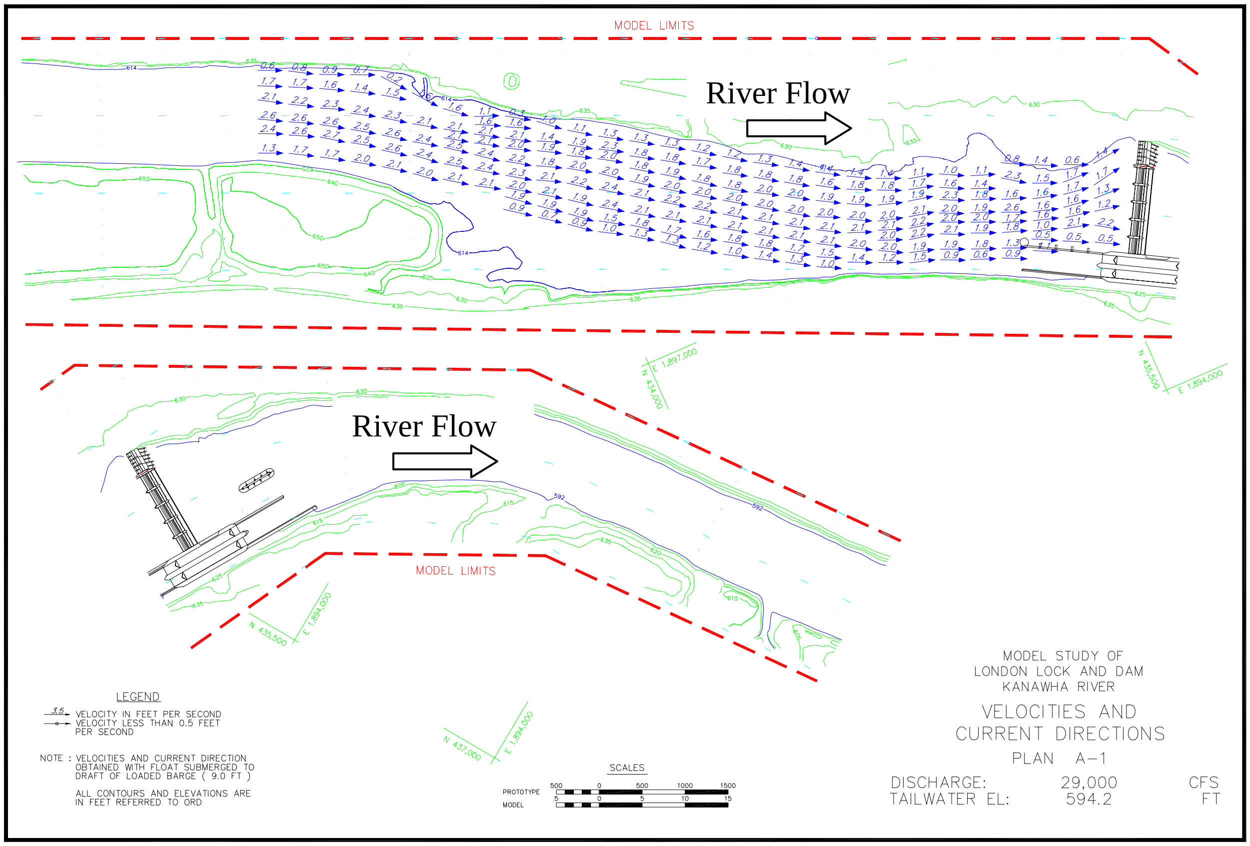

Figure C-19. Flow vectors from navigation model at London L&D

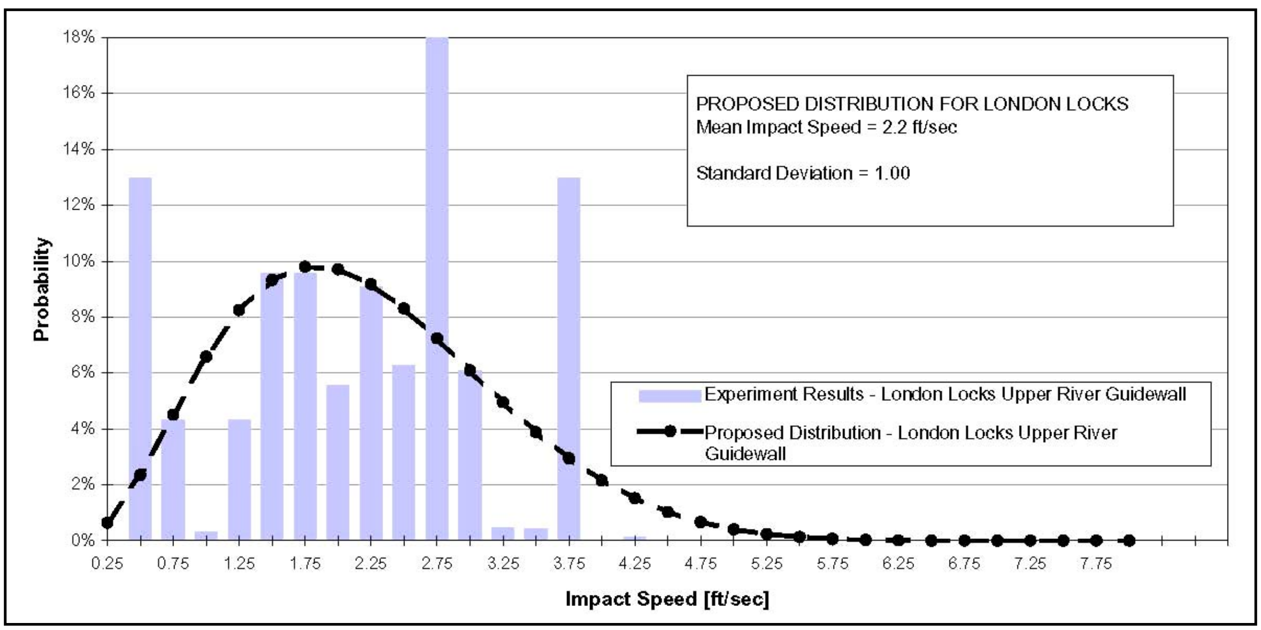

Figure C-20. Probability distribution for forward impact speed at London Locks upper landside guard wall

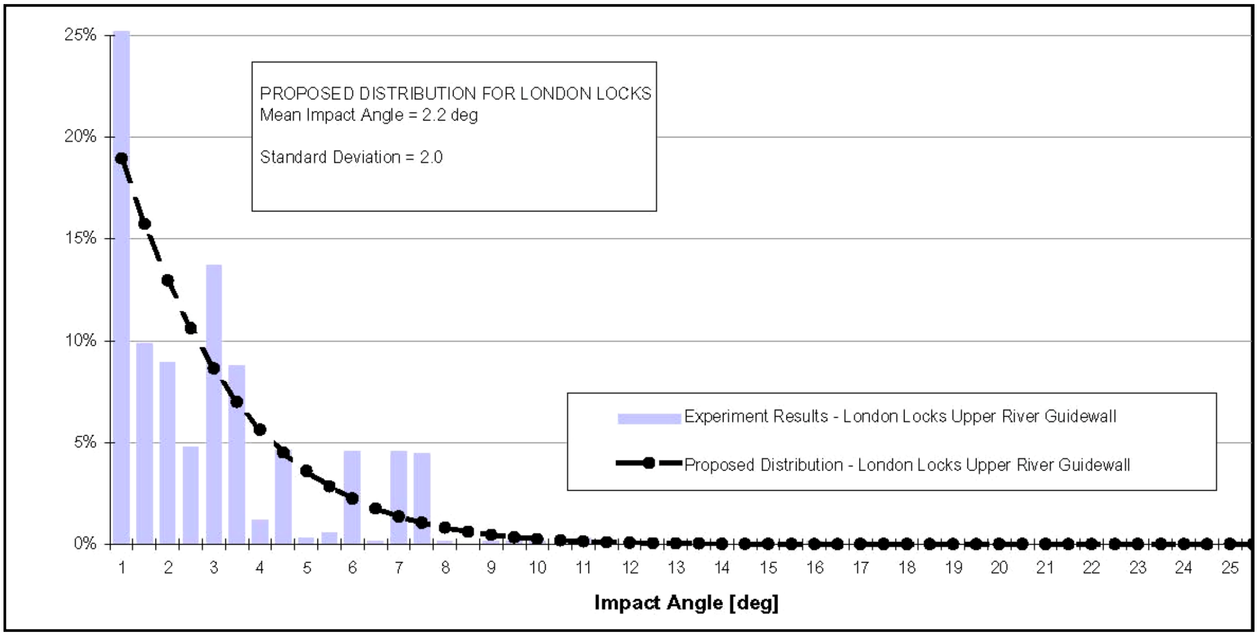

Figure C-21. Probability distribution for impact angle at London Locks upper landside guard wall

Table C-7
Lognormal Distribution Parameters for Impact Variables at London L&D Upper Landside Guard Wall

Design Structure	Variable	Mean	Standard Deviation	Minimum	Maximum
Upper landside guard wall	θ, deg	2.2	1.5	0	12
	V, ft/sec	2.2	0.6	0	10

f. Greenup Locks Approach Walls, Ohio River (Design Memorandum, Greenup Locks Approach Walls, Huntington District).

(1) As part of the Ohio River Main Stem Systems Study, a preliminary approach wall design was completed on the extension of the guide and guard walls at Greenup Locks. Currently, the existing upstream approach conditions are less than desirable due to crosscurrent problems. These crosscurrents are encountered by tows approaching the lock, which force them to flank toward the bank while their stern is being pulled toward the river. Figure C-22 shows the flow vectors from the navigation model at Greenup. In order to ensure an adequate landing zone for the tows, the approach walls will be lengthened and configured to allow a 366-m (1,200-ft) landing zone for each chamber. In order to facilitate the new approach to Greenup Locks after the landward existing 183-m (600-ft) lock chamber is extended, the following approach wall lengths were proposed for the project:

- Extend the existing upper river wall and upper middle wall by approximately 410 m (1,345 ft).
- Extend the existing lower land wall by approximately 335 m (1,184 ft) beyond the new lower landside lock monolith causing the wall to project 335 m (1,100 ft) beyond the new lower middle wall monolith.
- Extend the existing lower river wall by approximately 90 m (295 ft). The upper approach walls are proposed to be floating pontoons, which are restrained laterally by nose piers and pylons.

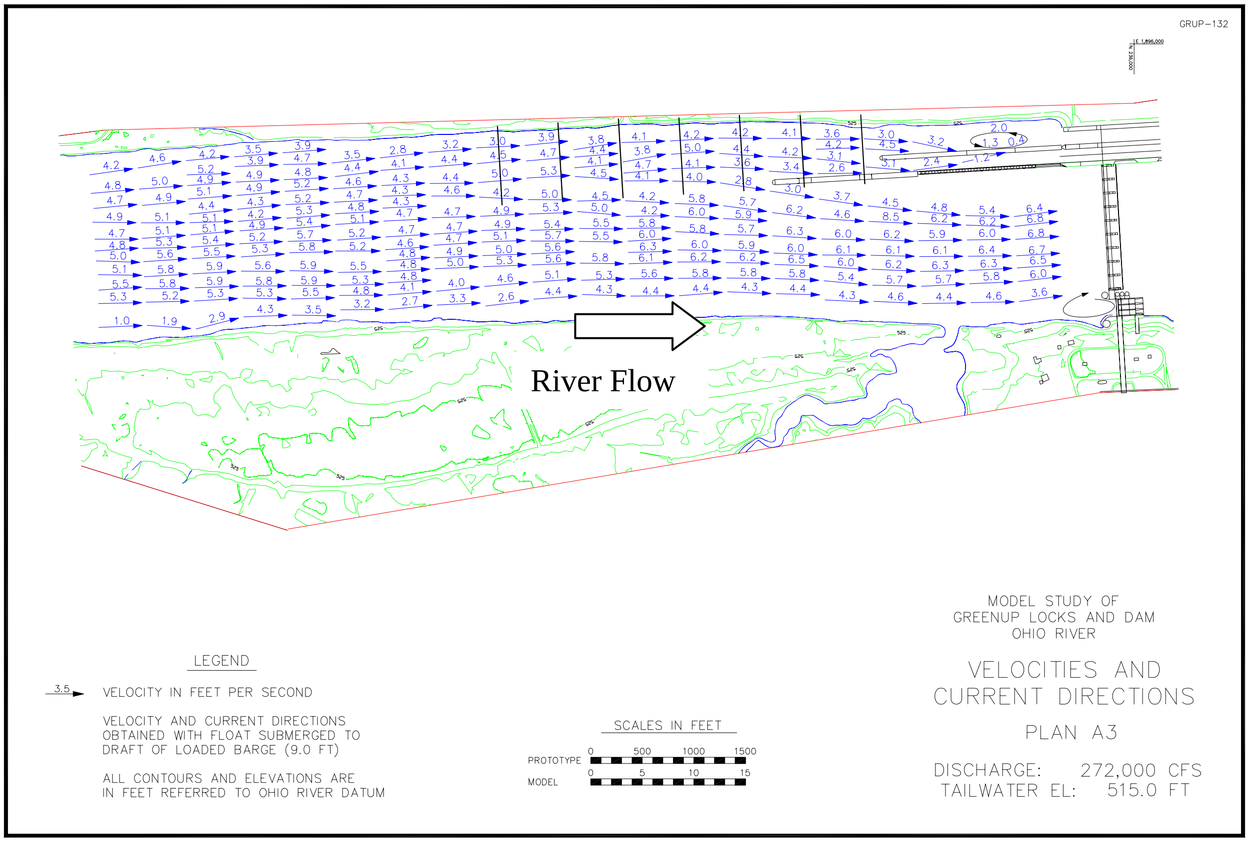

Figure C-22. Flow vectors from navigation model for Greenup L&D

(2) These approach layouts and the constraints on impact angles are shown in Figure C-23. The distributions for the weight of both downbound and upbound tows were taken from existing OMNI data and are shown in Figures C-24 and C-25, respectively. Since this design is for preliminary concept walls, navigation modeling was not completed as part of the Ohio River Main Stem Systems Study. However, it is anticipated that additional navigation modeling will be needed as the project rolls into the feasibility level design. As a part of the next design phase, scale model impact experiments will be conducted to better estimate the distributions for velocities and impact angle of downbound tows. For this preliminary design, the values for velocity are based on observations made during site visits and select time-lapse video records from the lock. The values for the angle of impact were based on site constraints as discussed above. Figures C-26 and C-27, respectively, present the proposed distributions for barge impact angle and impact velocity for the three floating walls at the project. Table C-8 summarizes the statistical parameters to be used in the preliminary design and sizing of approach walls.

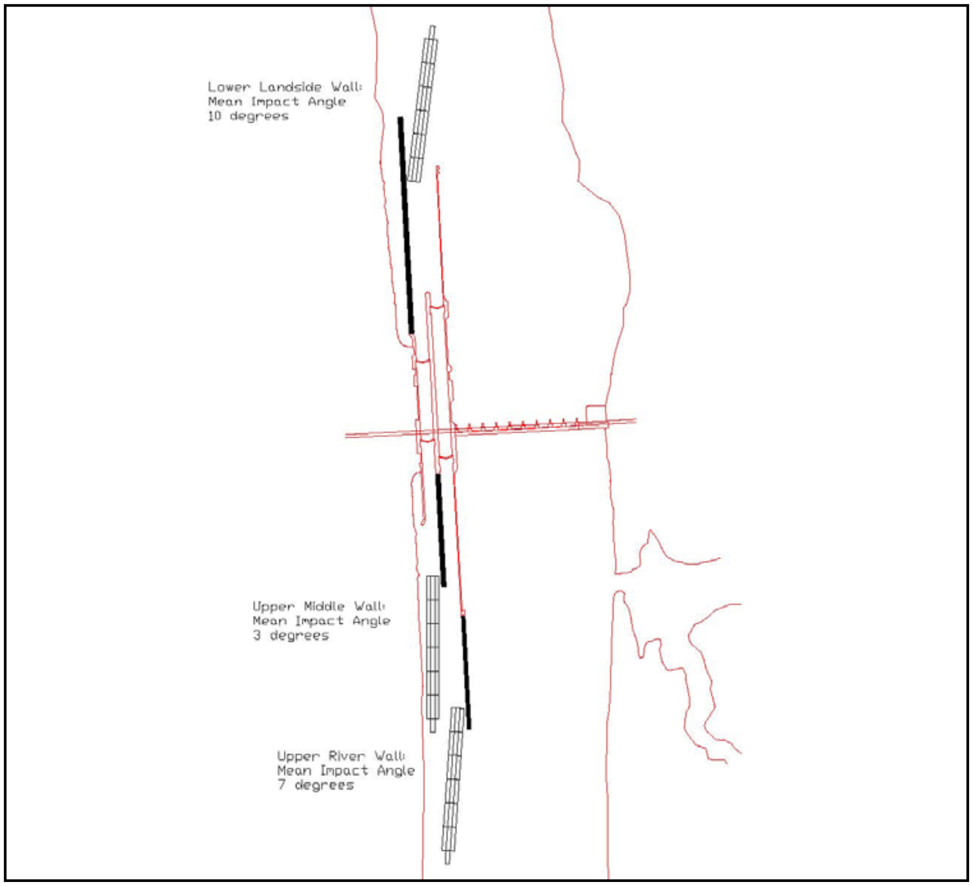

Figure C-23. Physical contraints on impact angles at Greenup Locks

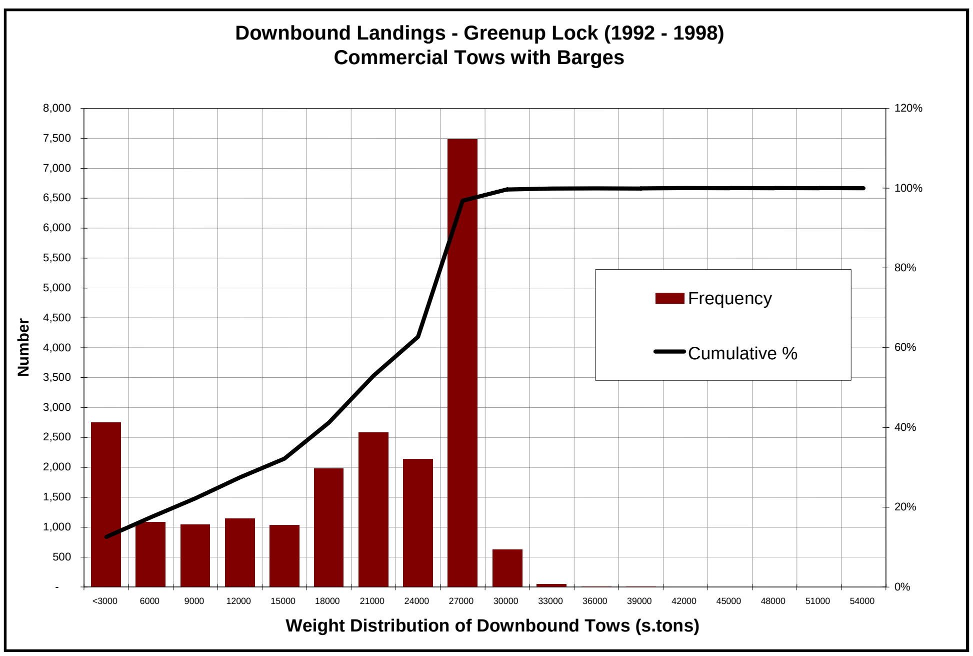

Figure C-24. Histogram of downbound tow weight distribution for Greenup L&D

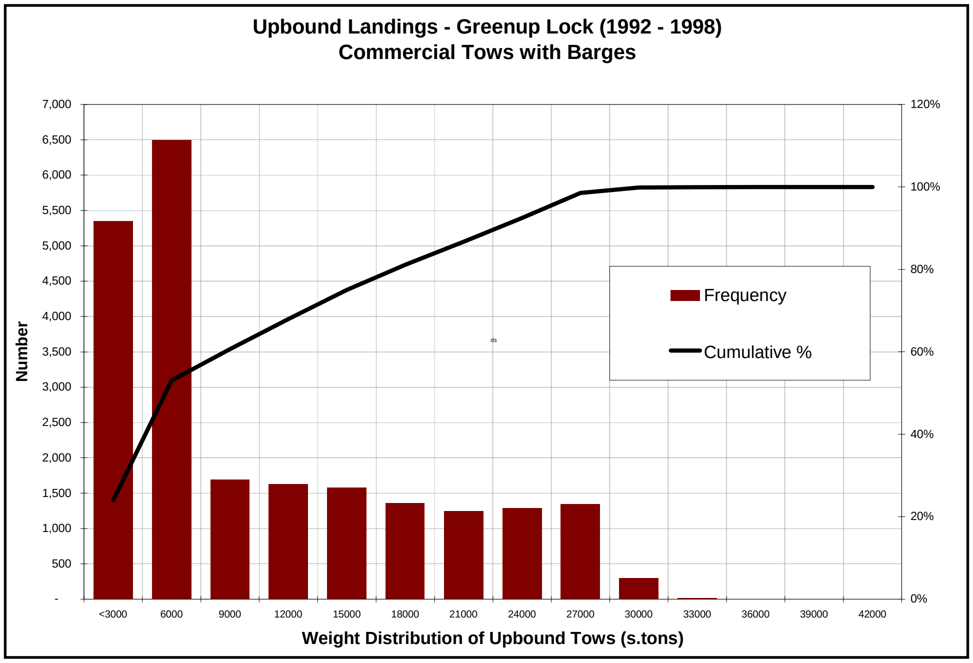

Figure C-25. Histogram of upbound tow weight distribution for Greenup L&D

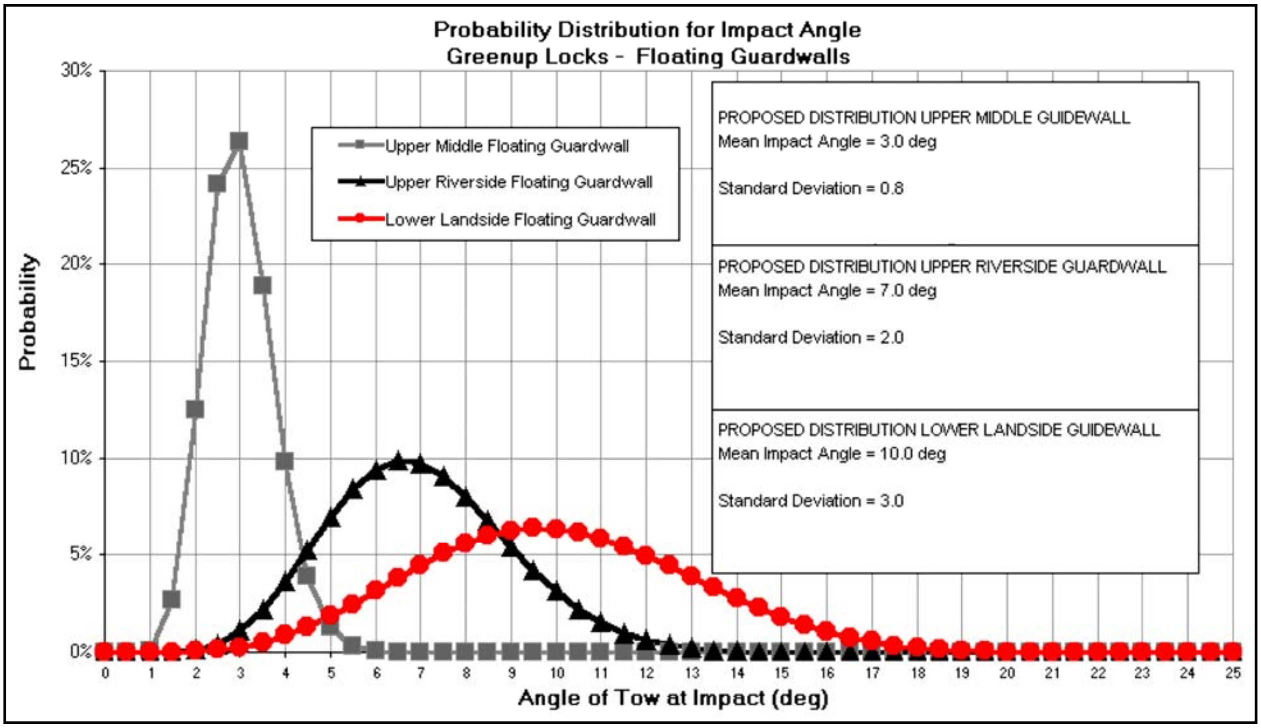

Figure C-26. Probability distributions for impact angle at Greenup L&D

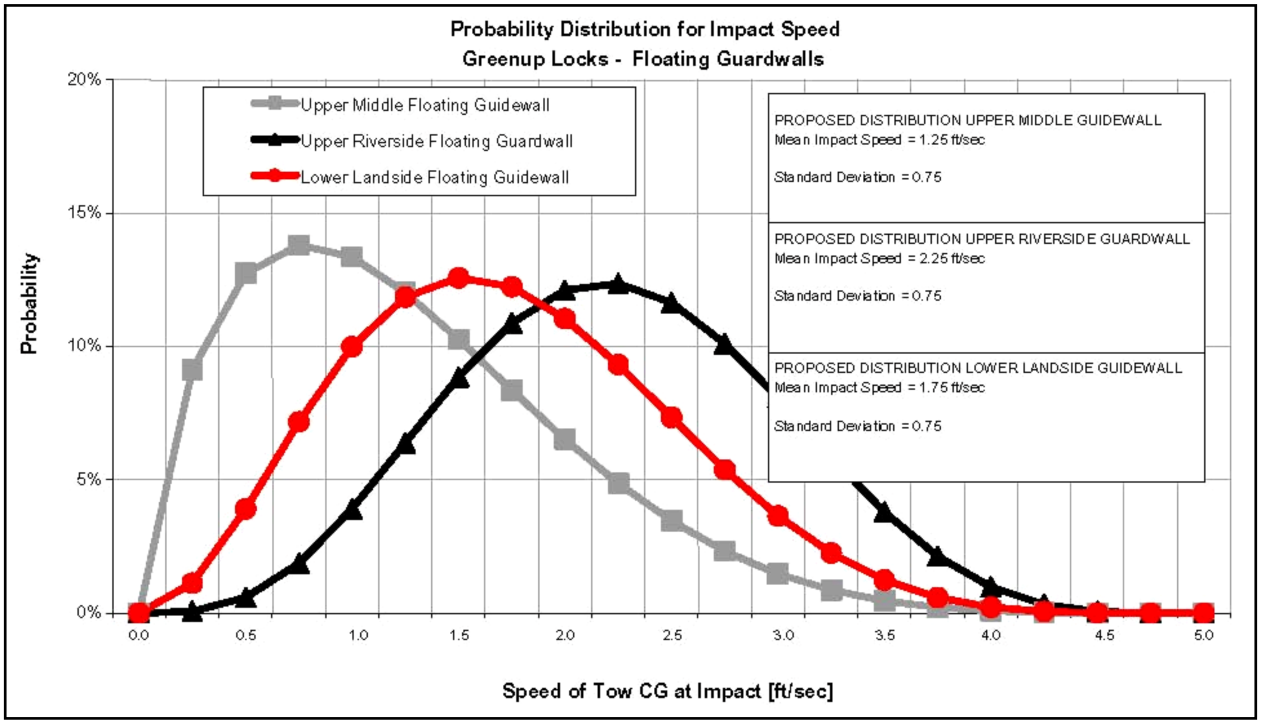

Figure C-27. Probability distributions for forward velocity at Greenup L&D

Table C-8
Lognormal Distribution Parameters for Impact Variables at Greenup L&D

Design Structure	Variable	Mean	Standard Deviation	Minimum	Maximum
Upper middle wall (downbound)	θ, deg	3.0	0.8	0	6
	V, ft/sec	1.25	0.75	0	5
Upper riverside wall (downbound)	θ, deg	7.0	2.0	0	22
	V, ft/sec	2.25	0.75	0	5
Lower landside wall (upbound)	θ, deg	10.0	3.0	0	25
	V, ft/sec	1.75	0.75	0	5

Appendix D
Examples of Probabilistic Barge Impact Analysis (PBIA) for Rigid Walls

D-1. Introduction

This appendix documents a few deterministic examples using the empirical formula discussed in paragraph B-2 as well as a detailed PBIA for an upper guide wall. The examples shown use typical design parameters (velocity, angle, and mass) used for design of navigation structures. The values selected also fit into the limitation of the empirical model.

D-2. Deterministic Example – Ohio River Project

This example is for the design of an approach wall for a new lock on the Ohio River. Based on present traffic predictions and navigation model testing at ERDC, a 15-barge tow and input parameters selected for the usual load case are as follows:

V_{0x} = 0.45 m/sec (1.5 ft/sec)
V_{0y} = 0.02 m/sec (0.05 ft/sec)
θ = 10 degrees
W_{barge} = 27,000,000 kg (30,000 short tons)

$(F_w)_{\max}$ = 0.435*(30000*2/32.2)*(1.5*sin (10) + 0.05*cos (10)) = 1,116 kN (251 kips)

The empirical correlation is expressed in specific non-SI (English) units. The result for $(F_w)_{max}$ can then be converted to SI (metric) units.

D-3. Deterministic Example – Mississippi River Project

This example is for the design of an approach wall for a new lock on the Mississippi River. Based on present traffic predictions and navigation model testing at ERDC, the 9-barge tow and input parameters selected for the usual load case are as follows:

V_{0x} = 0.6 m/sec (2.0 ft/sec)
V_{0y} = 0.02 m/sec (0.05 ft/sec)
θ = 15 degrees
W_{barge} = 12,000,000 kg (13,500 short tons)

$(F_w)_{max}$ = 0.435*(13500*2/32.2)* (1.5*sin (10) + 0.05*cos (10)) = 916 kN (206 kips)

D-4. Example of Probabilistic Barge Impact Analysis for an Upper Guide Wall

a. Introduction. This appendix details an example of a PBIA for a rigid upper guide wall at a lock and dam project. The purpose of the example is to show how to implement the methods and empirical model defined in paragraph B-2 of this ETL to determine the return periods for the design of the guide wall. This example uses data for impact angle and velocity from 1:120-scale model hydraulic experiments that were conducted at ERDC. The hydraulic conditions for the experiments were conducted under a flow regime of 708 cu m/sec (25,000 cu ft/sec). The data have been processed to determine the annual distributions and statistical parameters for the random variables in the PBIA. Data for loss of power, loss of control, and higher flow events are not included in this example. The combination of various annual events needs to be carefully considered and properly applied when performing a PBIA.

b. Results and processing of data from scale model tests. Site-specific data for the design of the upper guide wall for the lock were taken from a 1:120-scale hydraulic modeling at ERDC. Fifty experiments were conducted using a scale model rigid barge train (32 m (105 ft) wide by 297 m (975 ft)) and remote control towboat. The experiments utilized two different separate operators that simulated twenty-five approaches to the upper guide wall. These experiments were conducted at a river flow of 708 cu m/ sec (25,000 cu ft/sec). The raw data were recorded on a computer data acquisition system and post-processed to determine the x-velocity and y-velocity components of the barge and the angle of impact to the approach wall. Due to scaling effects of the water, the data for velocity and angle were processed prior to the barge impacting the wall. The data from the fifty experiments are presented in Table D-1. Figures D-1 through D-3 show the histograms from the experiments for longitudinal (V_{0x}) velocity, transverse (V_{0y}) velocity, and impact angle, respectively.

c. PBIA data.

(1) The data required for a PBIA are the longitudinal V_{0x} and transverse V_{0y} components, approach angles, and the mass for the barge train. These data must be processed to define the statistical parameters (i.e., mean, standard deviation, etc.) for the input to the PBIA model. The processing of the data may be done in the form of either a discrete distribution (a probability density for a specific value) or a continuous distribution (smoothed function that fits the data). These concepts will be explained in further detail using the data for this example.

(2) The weight of the barge train was taken from OMNI database (LPMS) records from 1984 to present for downstream barges transiting the adjacent lock chambers. From these data an annual histogram was processed using Excel to produce a discrete distribution of the data. The annual histogram for weight of the barge train is shown in Figure D-4. This figure shows that the data show two dominating masses (2,700,000 and 27,000,000 kg (3,000 and 30,000 tons)) for the traffic at this lock. This type of distribution is referred to as a double-humped camelback and is difficult to fit a continuous distribution. In this case, a discrete distribution at specific intervals (1,000 tons) is more reasonable and acceptable to use. The resulting input table for the discrete distribution for weight is shown in Table D-2.

(3) From the hydraulic model data in the previous sections, a continuous distribution and statistical parameters are fitted using a commercially available program. The program used for this example is called BestFit (Palisade Corporation 2003a). This program permits the fitting of data to numerous distributions and ranks them based on statistical testing procedures. For simplicity, a lognormal distribution was taken for the best fit to the raw data and the distributions are shown in Figures D-5 through D-7. Table D-3 shows a summary of the statistical parameters used for the PBIA.

(4) For this example, the PBIA model is developed in Microsoft Excel using a commercial Monte Carlo Simulation add-in package called @Risk (Palisade Corporation 2003b). @Risk allows the easy simulation of numerous combinations of annual events, which develop an annual probability distribution for the impact loads on the upper guide wall. For this example, 100,000 iterations were run to determine the distribution for the impact load. This annual distribution of impact load is then used to calculate the return periods for the impact loads to be used in design.

Table D-1
Raw Data from Scale Model Experiments at ERDC

	V_{0x}, ft/sec	V_{0y}, ft/sec	Angle, deg
Fitted Distribution	Lognormal (1.44, 5.5)	Lognormal (0.048, 0.083)	Lognormal (3.86, 2.31)
Experiment 1	1.04	0.214	5.61
Experiment 2	2.71	0.032	3.17
Experiment 3	0.05	0.024	4.27
Experiment 4	1.81	0.010	3.34
Experiment 5	1.07	0.012	2.49
Experiment 6	0.68	0.010	11.31
Experiment 7	8.32	0.022	3.80
Experiment 8	1.61	0.019	7.89
Experiment 9	0.14	0.008	2.93
Experiment 10	0.55	0.008	1.95
Experiment 11	0.62	0.027	2.96
Experiment 12	0.68	0.002	3.59
Experiment 13	0.05	0.018	1.15
Experiment 14	0.28	0.007	1.16
Experiment 15	4.02	0.007	1.09
Experiment 16	2.57	0.107	3.47
Experiment 17	0.20	0.055	3.88
Experiment 18	0.11	0.048	7.12
Experiment 19	0.48	0.027	5.92
Experiment 20	0.88	0.092	2.71
Experiment 21	0.95	0.023	1.36
Experiment 22	0.53	0.133	4.49
Experiment 23	0.23	0.001	1.50
Experiment 24	0.17	0.020	2.13
Experiment 25	0.47	0.075	2.40
Experiment 26	2.46	0.056	1.86
Experiment 27	0.04	0.018	4.00
Experiment 28	0.08	0.007	3.75
Experiment 29	1.91	0.043	0.44
Experiment 30	0.35	0.006	7.47
Experiment 31	0.80	0.072	2.42
Experiment 32	0.02	0.059	2.82
Experiment 33	2.82	0.039	2.11
Experiment 34	0.19	0.411	6.46
Experiment 35	0.28	0.016	8.56
Experiment 36	0.37	0.026	1.59
Experiment 37	1.91	0.018	1.61
Experiment 38	0.06	0.060	3.41
Experiment 39	3.01	0.060	1.65
Experiment 40	4.87	0.025	5.59
Experiment 41	0.02	0.014	2.78
Experiment 42	0.62	0.009	8.23
Experiment 43	0.20	0.049	2.15
Experiment 44	0.56	0.005	2.99
Experiment 45	0.55	0.024	3.50
Experiment 46	0.05	0.025	2.29
Experiment 47	0.02	0.006	1.69
Experiment 48	0.17	0.009	4.14
Experiment 49	0.10	0.432	2.99
Experiment 50	0.18	0.018	1.54

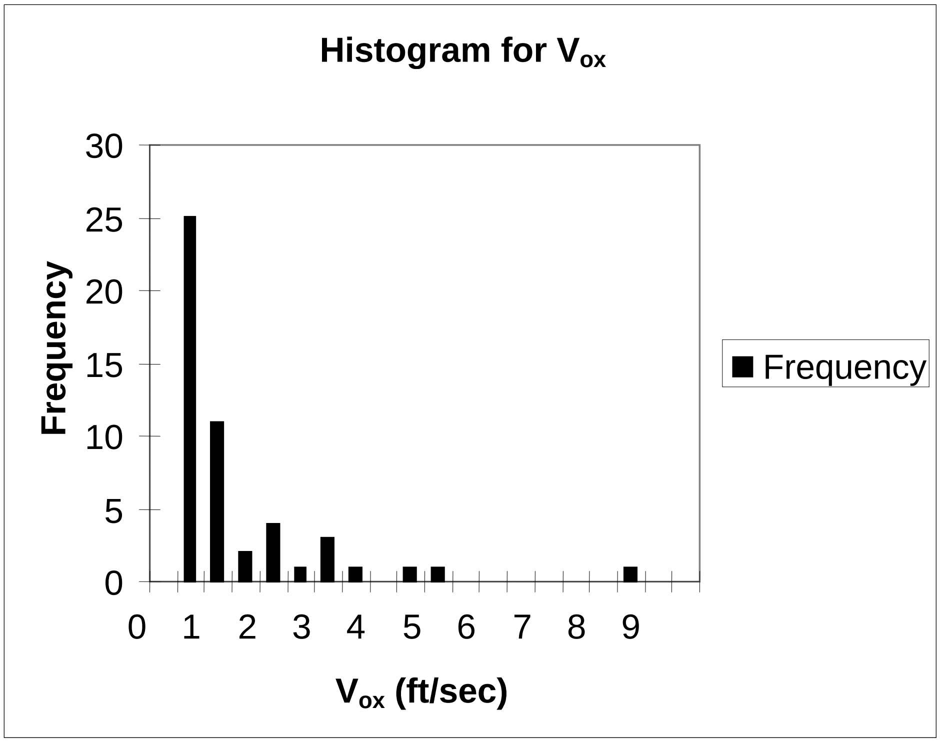

Figure D-1. Histogram for longitudinal x-velocity (V_{0x}) component

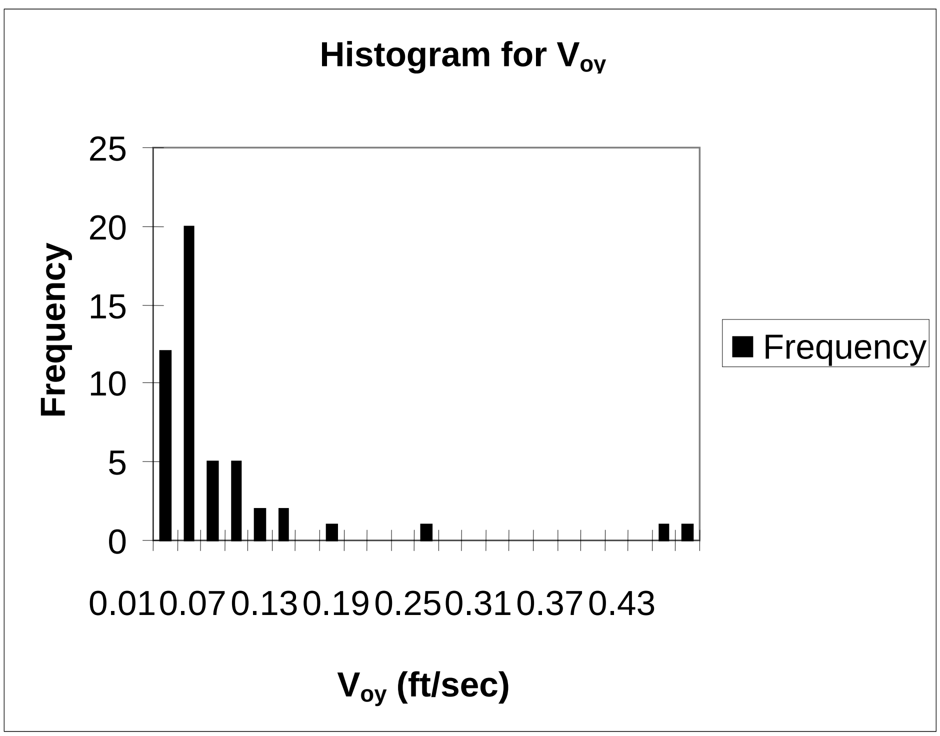

Figure D-2. Histogram for transverse y-velocity (V_{0y}) component

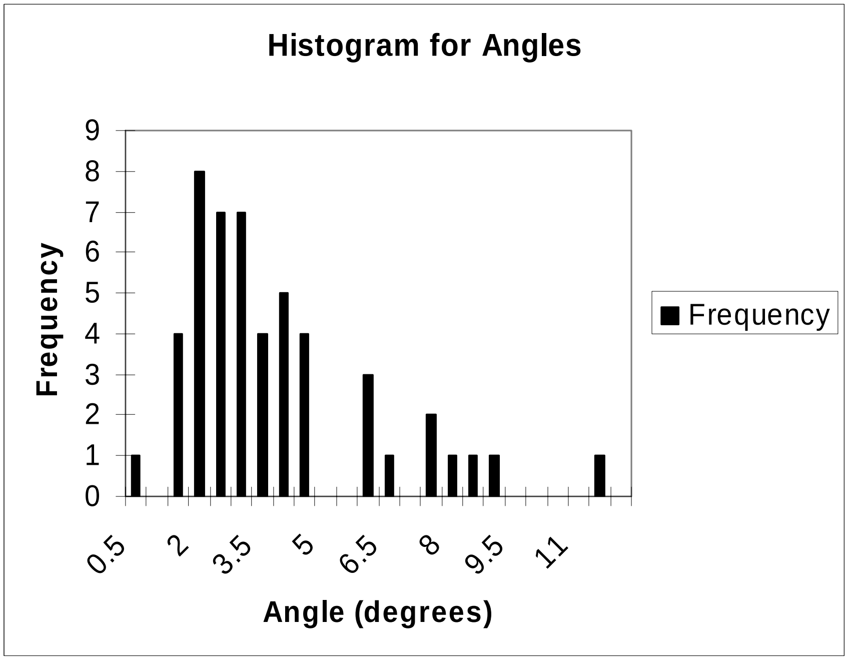

Figure D-3. Histogram for approach angles

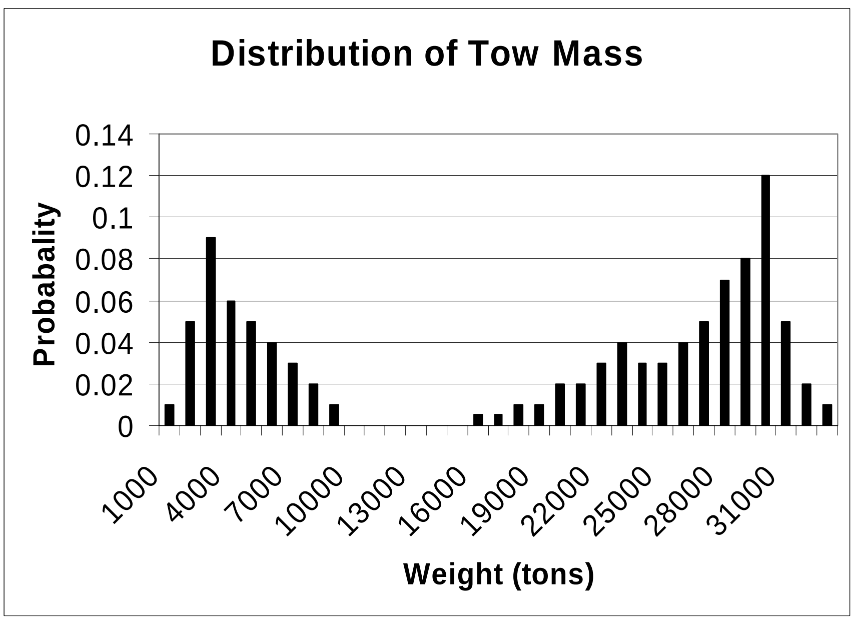

Figure D-4. Histogram of weights for barge trains

Table D-2
Discrete Function for Barge Train Weight

Weight, tons	Probability
1000	0.01
2000	0.05
3000	0.09
4000	0.06
5000	0.05
6000	0.04
7000	0.03
8000	0.02
9000	0.01
10000	0
11000	0
12000	0
13000	0
14000	0
15000	0
16000	0.005
17000	0.005
18000	0.01
19000	0.01
20000	0.02
21000	0.02
22000	0.03
23000	0.04
24000	0.03
25000	0.03
26000	0.04
27000	0.05
28000	0.07
29000	0.08
30000	0.12
31000	0.05
32000	0.02
33000	0.01

Sum of Probabilities = 1

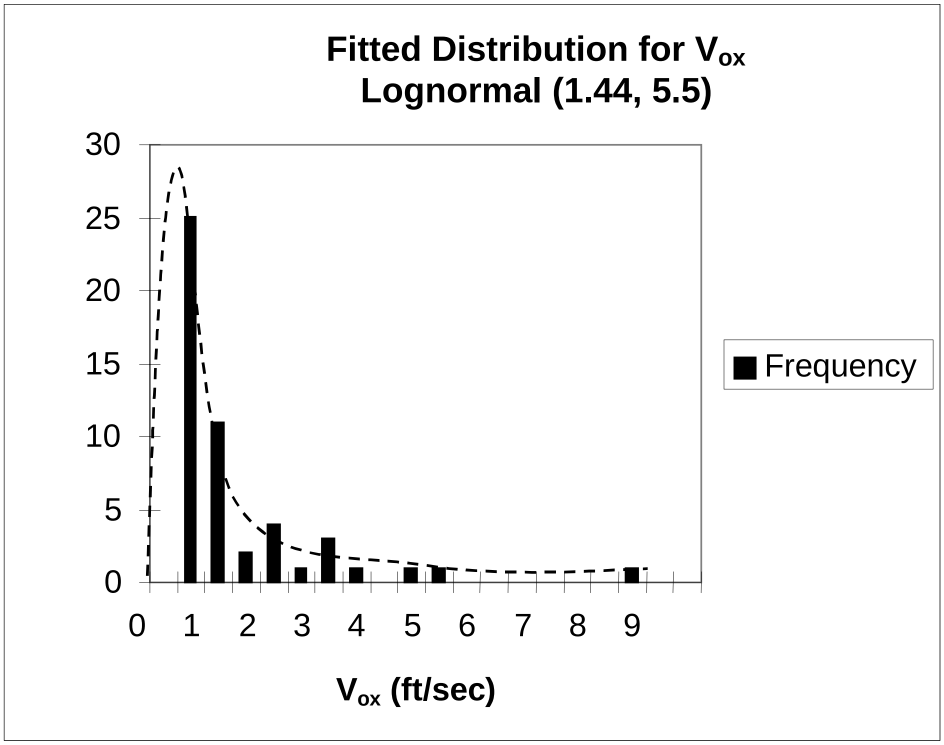

Figure D-5. Histogram of longitudinal velocity from experiments (note: lognormal distribution is fitted dashed line)

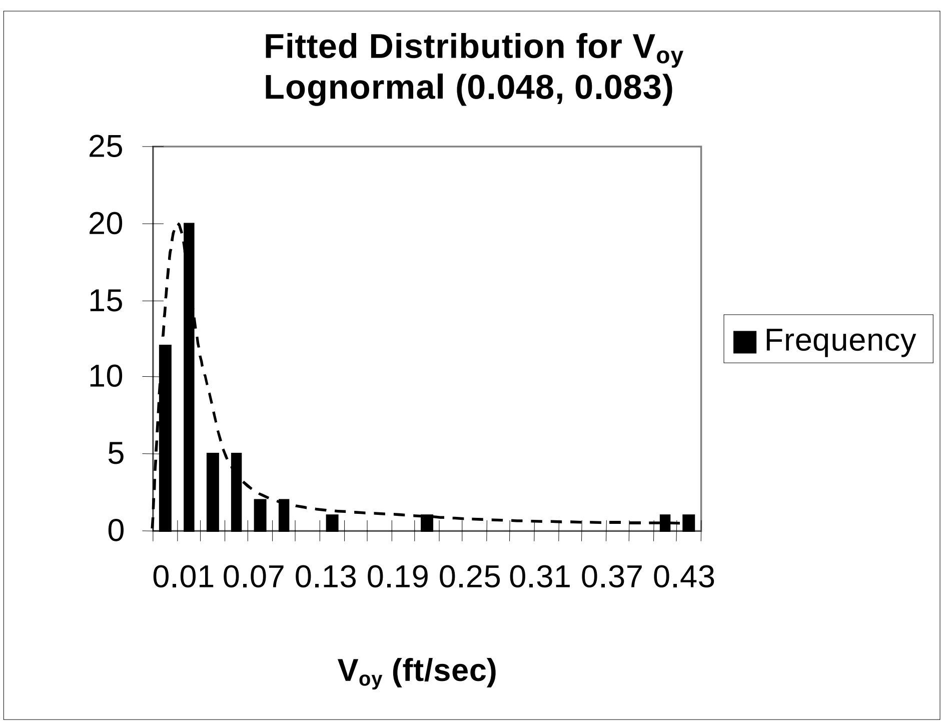

Figure D-6. Histogram of transverse velocity from experiments (note: lognormal distribution is fitted dashed line)

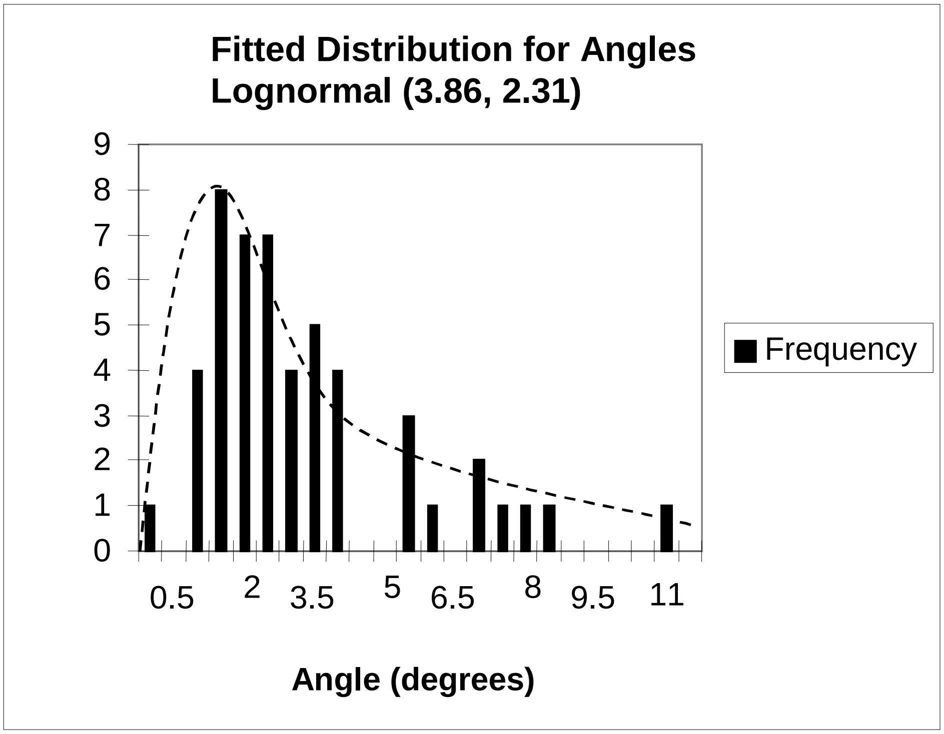

Figure D-7. Histogram of impact angle from experiments (note: lognormal distribution is fitted dashed line)

Table D-3
Fitted Distributions for Scale Model Data

	Distribution Type	Mean	Standard Deviation	Truncation
Longitudinal x-velocity	Lognormal	0.439 m/sec (1.44 ft/sec)	1.67 m/sec (5.5 ft/sec)	2 m/sec (6 ft/sec)
Transverse y-velocity	Lognormal	0.0146 m/sec (0.048 ft/sec)	0.026 m/sec (0.083 ft/sec)	0.3 m/sec (1 ft/sec)
Angle (degrees)	Lognormal	1.176 m/sec (3.86 ft/sec)	0.704 m/sec (2.31 ft/sec)	None

(5) The spreadsheet developed for this example uses the empirical equation discussed in paragraph B-3 of this ETL. The data input to the cells for this example are shown in Figure D-8. @Risk uses the calls of "RiskLognorm" within a cell to define the lognormal random variable with its mean and standard deviation. The "RiskTruncate" command limits the sampling of the distribution above those values. The output for F_m uses the "RiskOutput" command and the empirical equation follows the name. Uncertainty in the empirical model is not included in this example for simplicity. Based on the processing of the data to define the empirical equation as discussed in Appendix E, the standard deviation (or error) in the empirical model is 351 kN (±79 kips). This would need to be included in the PBIA as approximately a ±10 percent coefficient of variation during the simulation of impact force results. These variations of the model would be represented by a cone shape running from 0 to 800 kips, which is shown in Appendix E, Figure E-3. These values input to the spreadsheet cells reflect the values from Table D-3.

Olmsted PBIA Example Using Empirical Method

Mass Distribution		
	=RiskDiscrete(Mass!A33:A65,Mass!B33:B65)	short tons
Angle		
	=RiskLognorm(3.86,1.31)	degrees
Velocity		
Vox	=RiskLognorm(1.44,5.5,RiskTruncate(0,6))	feet per second
Voy	=RiskLognorm(0.048,0.083,RiskTruncate(0,1))	feet per second
Vn	=(B14*SIN(B10*PI()/180)+B15*COS(B10*PI()/180))	feet per second
Force		
Fm	=RiskOutput("Impact Force") + 0.435*(B6*2/32.2)*(B14*SIN(B10*PI()/180)+B15*COS(B10*PI()/180))	kips

Figure D-8. Excel and @Risk spreadsheet cell formulas

d. PBIA results.

(1) The statistical results from the PBIA are shown in Table D-4. This table shows the minimum, maximum, mean, and standard deviation from the simulation data for the impact force. However, since the PBIA is performed to calculate the return periods, the output needs to be expressed in terms of either the histogram, cumulative probability distribution, or the corresponding percentiles of the impact loads. These are all derived from the output or graphing capabilities from with the @Risk simulation program.

Table D-4
Statistics from PBIA Example

Statistic	Force, kips
Minimum	0.05
Maximum	978.89
Mean	47.21
Std Dev	67.52

Note: To convert force to kilonewtons, multiply by 4.448.

(2) The histogram shows the range and distribution of expected annual impact forces. Figure D-9 shows the histogram for this example. The histogram shows that a majority of the impact forces (over 90 percent as shown in Figure D-9) from the simulation are below the mean value of 209.95 kN (47.2 kips). From this histogram, a cumulative probability distribution of impact forces can be fit. Figure D-10 shows the cumulative probability distribution for the PBIA. The cumulative probability distribution is used to determine the percentage of distribution that is below a specified level. Figure D-10 shows that 90 percent of impact values below the mean value and 10 percent of the distribution lie above that value.

(3) For a PBIA, the simplest way to determine the return period is to use percentiles for the distribution of annual impact forces. Percentiles are defined as the percentage of annual impact force that occurs at or below that impact force. The resulting percentiles can be used to determine the Probability of Exceedence $P(E)$, which is the converse of the percentile such that both should add up to unity. The return period RT can be determined by using the equation

$$RT = 1/(1\text{-Percentile (in decimal)})$$

$$= 1/P(E)$$

The values for this PBIA example are shown in Table D-5.

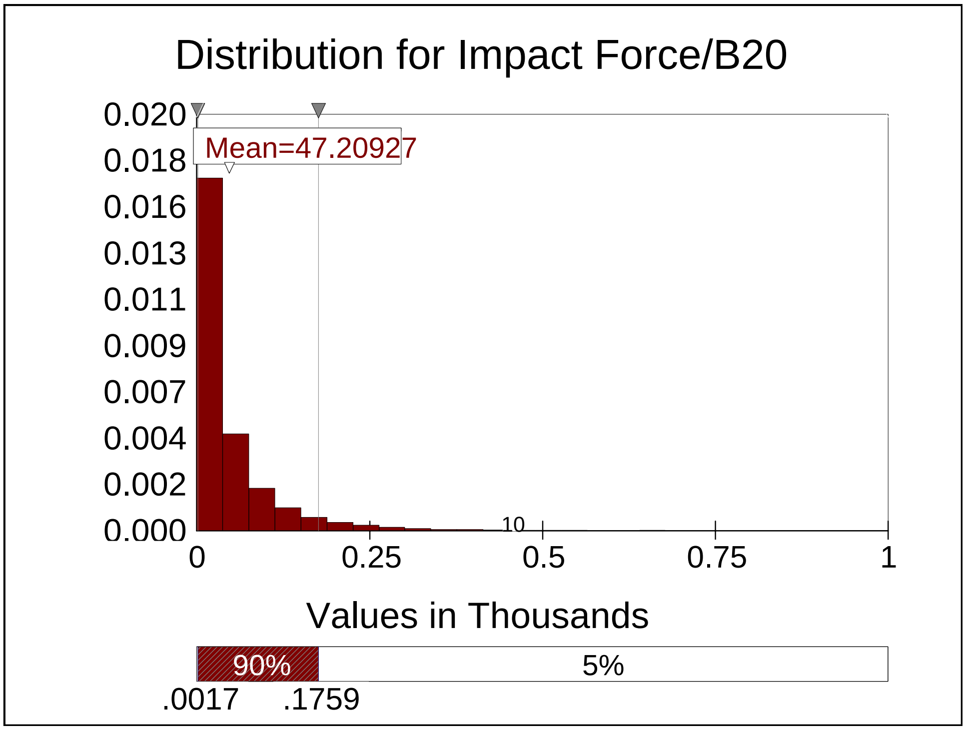

Figure D-9. Histogram of impact forces

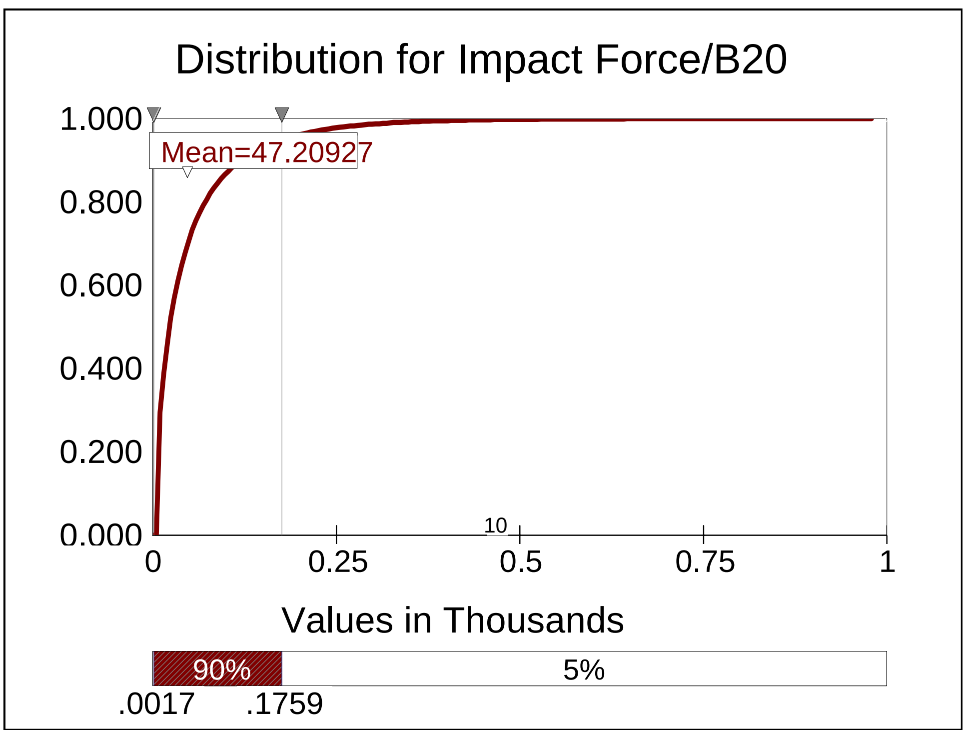

Figure D-10. Cumulative probability distribution for impact forces

Table D-5
Percentiles for Impact Load

Percentile	Return Period years	Impact Force kips
10%	1.11	3.02
20%	1.25	6.03
30%	1.43	10.07
40%	1.67	15.52
50%	2	22.79
60%	2.5	32.97
70%	3.33	47.68
80%	5	71.45
90%	10	120.13
95%	20	175.94
96%	25	197.26
97%	33.33	223.14
98%	50	260.89
99%	100	327.72
99.25%	133.33	357.13
99.50%	200	395.44
99.80%	500	508.99
99.90%	1000	575.08
99.98%	5000	731.97
99.99%	10000	796.68

Note: To convert impact force to kilonewtons, multiply by 4.448.

e. Design of upper guide wall for barge impact.

(1) Based on the criteria for return period discussed in paragraph B-3 and Table B-1 of this ETL, return periods for the impact design for the upper guide wall are selected as shown in Table D-6. These return periods were selected for this design due to the variations in the experiment data for the different load conditions. The usual and extreme data have a larger uncertainty since there were limited number of experiments that fit those load levels. Most of the experimental data fell closer to the unusual load condition, so the return period selected was near the midpoint of the two bounds for that load condition as shown in Table B-1.

Table D-6
Design Force for Upper Guide Wall

Event Loading	Design Return Period, years
Usual	10
Unusual	150
Extreme	500

(2) From the percentiles and data, a graphical representation of the return periods and loads is shown in Figure D-11. This graph shows the impact loads for each return period selected for the design. These impact forces selected do not include the load factors for each of the design cases as defined in EM 1110-2-2104. A summary table with the load factors included for the design of the wall is shown in Table D-7.

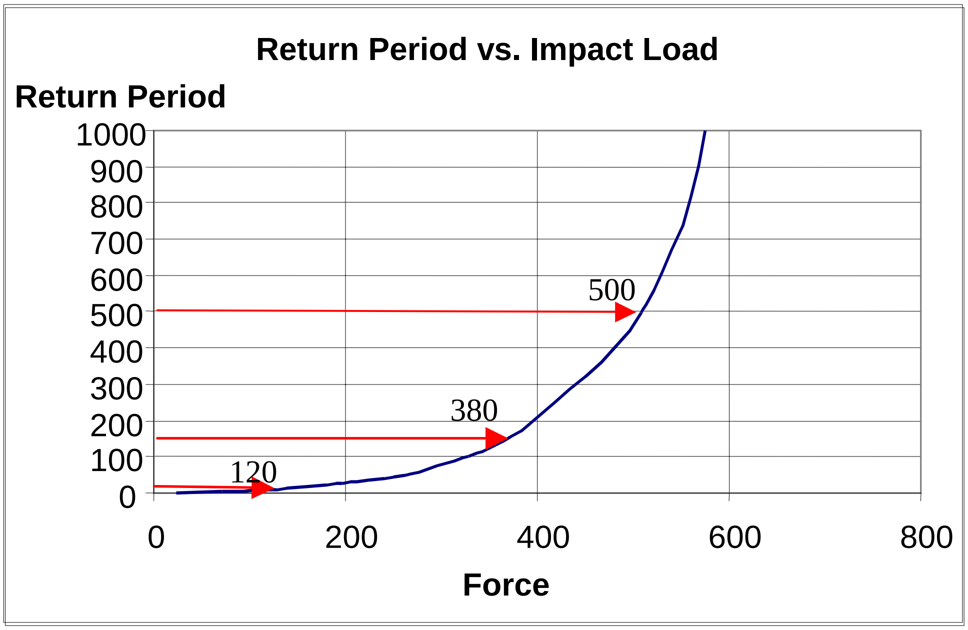

Figure D-11. Return period versus impact load for upper guide wall

Table D-7
Factored Design Force for Upper Guide Wall

Event Loading	Design Return Period years	Impact Force, kips	Factored Impact Force kips
Usual	10 years	120	204
Unusual	150 years	380	532
Extreme	500 years	510	561

Note: To convert impact force to kilonewtons, multiply by 4.448.

Appendix E
Empirical Method for Barge Impact Analysis for Rigid Walls

E-1. Introduction

In this appendix, an empirical correlation between the maximum force normal to the wall and the linear momentum normal to the wall is presented. The maximum force F_w used in this correlation was obtained from the models presented in Chapter 5 of Arroyo, Ebeling, and Barker (2003). Recall that no damage occurred to the barge and no lashings failed during impact testing for the eight impact experiments used to derive the empirical correlation described in this appendix. The experiments were also conducted to eliminate both the transverse velocity component V_{0y} and the rotational component. These both were negligible in the results from the data processing.

E-2. Development of Empirical Correlation from Full-Scale Experiments

a. Using values for $F_w(_{max})$, the maximum normal force F_w, and the linear momentum normal to the wall given in the last column of Table E-1, a best-fit straight line was calculated for the eight experiments. The velocity V_{0x} listed in the third column of Table E-1 acts in the local barge x-axis. This approach relates the F_w obtained from the energy method directly to the linear momentum. Figure E-1 shows the velocity vector transformation from local (barge) axis) to global (wall) axis used for the experiments. It is important to mention that only one data point of the whole F_w time-history for each of the eight experiments was used to develop this empirical correlation. The velocity normal V_{norm} and velocity parallel V_{par} shown in Figure E-1 relate the coordinate system of the barge train to the coordinate system of the wall.

b. A least squares regression procedure was used to develop the best-fit straight line through the eight data points (for the eight impact experiments) for the Figure E-2 empirical correlation. The line was assumed to start at the origin (i.e., no intercept term was used for the linear equation). The resulting best-fit equation for this set of eight data values is $(F_w)_{max} = 0.435 * m * V_{0x} * \sin\theta$, where *m* is the mass in tons. That is, a coefficient times the linear momentum normal to the wall determines the maximum force normal to the wall.

Table E-1
$(F_w)_{max}$ Empirical Correlation

Exp No.	Approach Angle deg	Velocity V_{0x} ft/sec	Mass k-sec^2/ft	Measured $(F_w)_{max}$ kips	Mvsin(θ) k-sec
29	12.63	2.2	1,865.59	286.63	897.42
30	12.19	2.35	1,865.59	369.15	925.73
31	10.60	1.61	1,865.59	236.2	552.52
37	10.29	1.95	1,865.59	327.27	649.84
38	11.94	1.83	1,865.59	230.29	706.32
39	14.12	1.61	1,865.59	271.07	732.74
41	8.76	2.86	1,865.59	419.37	812.59
42	17.48	1.83	1,865.59	577.44	1,025.48

Note: To convert kip-sec^2/ft to MN-sec^2/m, multiply by 0.135. To convert k-sec to MN-sec, multiply by 0.004450 MN-sec.

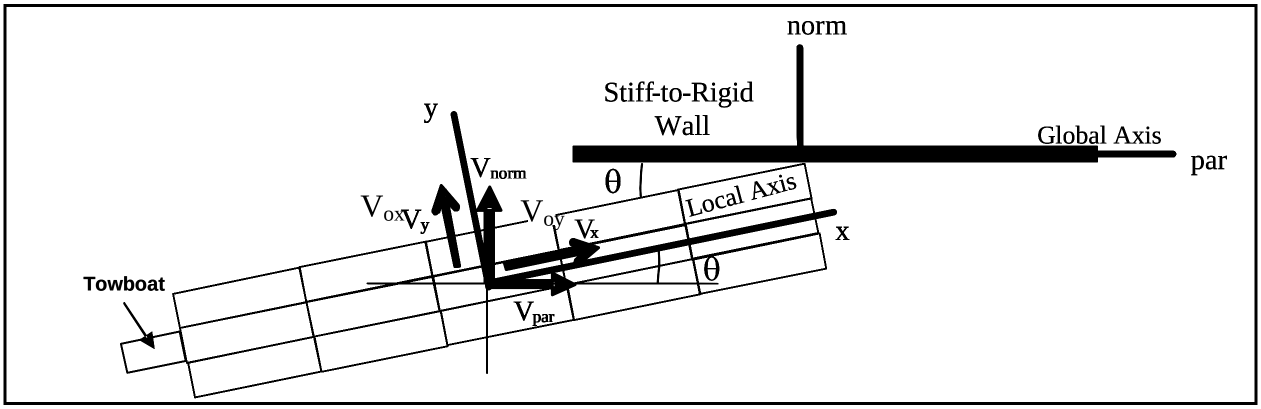

Figure E-1. Barge train and velocity vector transformation from local (barge) to global (wall) axis

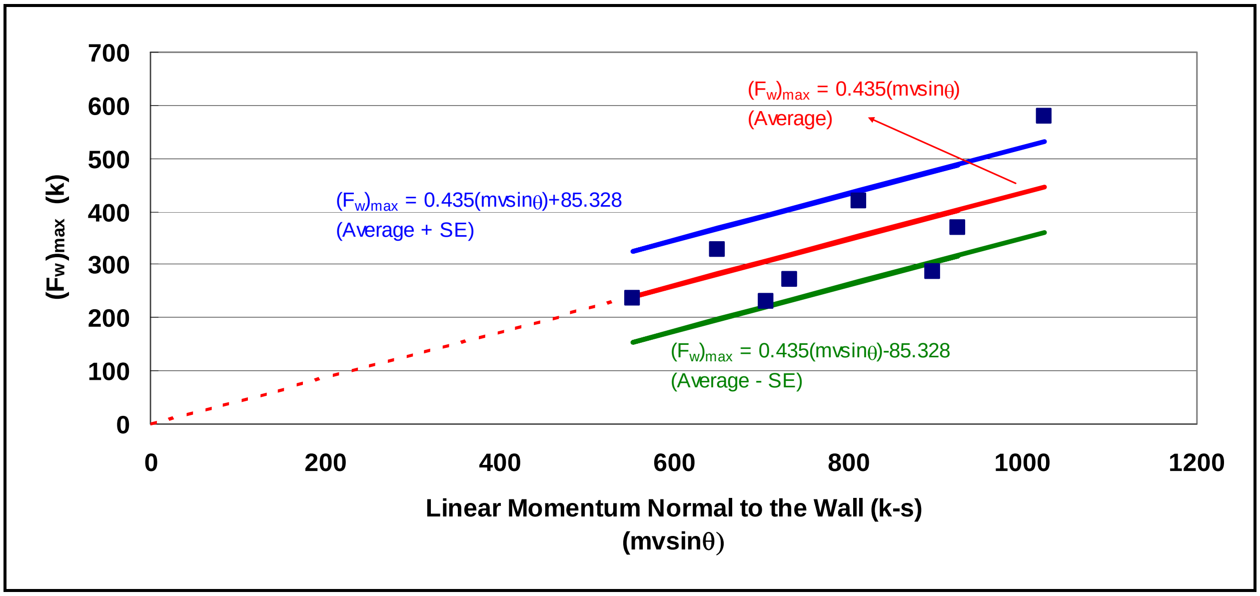

Figure E-2. Empirical correlation between *$(F_w)_{max}$* and linear momentum normal to the wall

c. The greater the magnitude for the linear momentum, the larger will be the maximum value for the impact force normal to the wall. This correlation is based on low-velocity, shallow-impact (up to 21.1 deg) experiments that, by definition, do not account for factors that manifest themselves at higher velocities. Additionally, no damage occurred to the barge train, and no lashings broke during these eight impact experiments. Therefore, it is deemed that this empirical method is applicable to a barge train that has a velocity normal to the wall up to and not exceeding 0.17 m/sec (0.57 ft/sec (0.6 km/hr (0.39 mph))) with no damage occurring during impact events, for impact angles up to 21.1 deg, for a barge train with a linear momentum normal to the wall between 2.9 and 4.6 MN-sec (649.84 and 1,025.48 k-sec). The equation to determine the maximum force normal to the wall using the empirical correlation is

$$(F_w)_{max} = 0.435*m*(V_{0x} * \sin\theta + V_{0y} * \cos\theta)$$

where the units for the mass, velocity, and maximum F_w are k-sec^2/ft, ft/sec, and kips, respectively. Note that no hydrodynamic added mass is assigned to m when using this relationship.

d. The maximum normal force $(F_w)_{max}$ by the empirical correlation is equal to the reaction force provided by the lock wall on the barge train during the impact. Note that the mass used to develop the correlation of linear momentum normal to the wall with values of $(F_w)_{max}$ is the mass of the barge train and does not include the computation of any hydrodynamic added masses. However, the values of $(F_w)_{max}$ in Table E-1 (which are derived from the field test data) reflect the effects of the external forces of barge train (due to engine), drag force, and helper boat force acting on the barge train as well as the effects of the hydrodynamic masses and the inertia of the barge train mass decelerating during impact.

E-3. Summary of Results

A summary of the values for the maximum impact force normal to the wall $(F_w)_{max}$ for the eight full-scale, controlled barge impact experiments shown in Table E-1 compared to the empirical equation is given in Table E-2. For example, the energy method or the equilibrium with a fixed coefficient of friction value (= 0.6) for the full-scale, controlled barge impact experiment (No. 29) produces an $(F_w)_{max}$ value of 1,274.99 kN (286.63 kips), and the best-fit straight line of the empirical correlation produces an $(F_w)_{max}$ value of 1,736.49 kN (390.38 kips). This corresponds to a 36 percent overprediction by the best-fit straight line of the empirical correlation approach. The maximum force normal to the wall $(F_w)_{max}$ computed using the best-fit straight line of the empirical correlation differs from the maximum force $(F_w)_{max}$ values presented in Table E-2 by a 23 percent underprediction to a 36 percent overestimate for these eight impact tests. Based on the linear regression of the data point in Table E-2, standard error or standard deviation of the model is 351.4 kN (±79 kips). This model variability should be accounted for in the empirical equation by including a ±10 percent coefficient of variation to the linear equation defined above. Figure E-3 shows the cone-shaped variation in the empirical results that should be included in the PBIA from 0 to 3,558 kN (800 kips).

Table E-2
$(F_w)_{max}$ Empirical Correlation (Mass = 1865.59 k-sec^2/ft)

Exp No.	Approach Angle deg	Velocity V_{0x}, ft/sec	Measured $(F_w)_{max}$ kips	Empirical $(F_w)_{max}$ kips	Percent Difference
29	12.63	2.2	286.63	390.38	36
30	12.19	2.35	369.15	402.69	9
31	10.60	1.61	236.2	240.35	2
37	10.29	1.95	327.27	282.68	-14
38	11.94	1.83	230.29	307.25	33
39	14.12	1.61	271.07	318.74	18
41	8.76	2.86	419.37	353.48	-16
42	17.48	1.83	577.44	446.08	-23

Note: To convert ft/sec to m/sec, multiply by 0.3048. To convert kips to kilonewtons, multiply by 4.448.

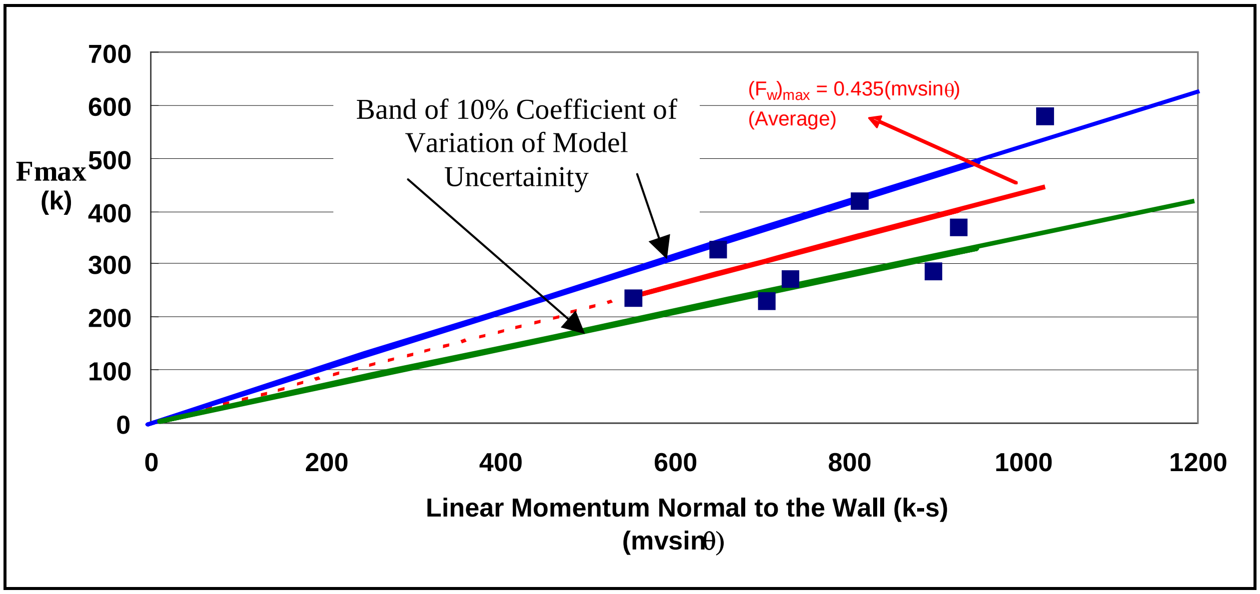

Figure E-3. Cone shape of coefficient of variation of model uncertainity

Appendix F
Field Experiments

F-1. Introduction

Three series of full-scale impact experiments were completed under the Innovations for Navigation Research and Development Program at ERDC. These experiments have been termed prototype, full-scale, and crushing impact experiments. These experiments were conducted to assist with estimating actual impact loads using typical inland waterway barge trains and to assist with developing analytical or numerical models for barge impact design of navigations structures.

F-2. Prototype Barge Impact Experiments

a. The prototype barge impact experiments were conducted on an old lock wall at Allegheny River Lock and Dam 2 in Pittsburgh, Pennsylvania. These experiments were termed prototype because this type of full-scale experiment using an inland waterway barge train has never before been attempted. The goals of these prototype experiments were to learn how to quantify and measure barge impact forces as well as understand the complexity of the barge-wall system during impact. The observations and results from these prototype experiments are discussed and documented further in Patev, Barker, and Koestler (2003b).

b. These experiments utilized four standard (8.2 by 59 m (27 by 195 ft)) open hopper rake barges. The barges were drafting as 2.6 m (8-1/2 ft) and had a combined mass of around 3,600,000 kg (4,000 short tons). Twenty-eight impact experiments were performed on a rigid massive concrete wall, and seven tests on frictionless Ultra-High Molecular Weight plastic fenders. The Ultra-High Molecular Weight fenders were used to investigate the redistribution of the barge energy and direction during impact. The experiments utilized 15 different instrumentations recorded on 28 channels on the barge train and land wall. The instrumentation included accelerometers and strain gauges on the lead corner barge as well as clevis pin load cells spliced into the lashings. These clevis pin load cells measured the changes in tensile force in the lashing parts upon impact. A multi-unit Differential Global Positioning System also measured the velocities (normal and tangential), impact angle, and rotation of the barge train during impact. A high-speed camera (100 frames per second) and a videotape camera were set up to document the interaction of the barge-wall system upon impact. Overall, these experiments were very valuable in providing a better understanding of the dynamics of the barge-wall system and contributed vital data that could be used to plan and design the full-scale barge impact experiments.

F-3. Full-Scale Barge Impact Experiments

a. The full-scale barge impact experiments were conducted on a lock wall at Robert C. Byrd Lock and Dam (Old Gallipolis Lock) in Gallipolis Ferry, West Virginia. The primary goal of these experiments was to measure the actual impact forces normal to the wall using a load-measuring device. The focus of these experiments was to measure the baseline response of an inland waterway barge, quantify an MDOF system during impact, and investigate the use of energy-absorbing fenders. The observations and results from these full-scale experiments are discussed further in Patev, Barker, and Koestler (2003a).

b. The full-scale experiments used a 15-barge commercial barge train. The barges were jumbo open hopper rake barges (11 by 59 m (35 by 195 ft)) and were ballasted with anthracite coal to a draft of 3 m (9 ft). The total mass of the barge train was approximately 27,000,000 kg (30,000 short tons). The use of the barges and a 2,088-kW (2,800-horsepower) towboat, the MS *Jeffery V. Raike*, was arranged under a partnership agreement with American Electric Power River Transportation Division of Lakin, West Virginia. A helper boat was also needed in case of emergency with the prime vessel or breakup of the barge train during impact. The helper boat, an 820-kW (1,100-horsepower) towboat, the MS *Quaker State,* was supplied by Kanawha River Towing of Point Pleasant, West Virginia. The 15-barge tow and helper boat are shown in Figure F-1.

Figure F-1. Barge train used for full-scale experiments

c. Forty-four impact experiments were successfully conducted on both the rigid concrete upper guide wall (baseline and load-measuring device) and on the prototype fendering system (baseline and load-measuring device). A matrix of the required angles and velocities was assembled for the comparison between the baseline and load-measuring experiments on both the concrete and prototype fendering systems. This matrix was successfully filled for each impact case during these 44 experiments. The final matrix contained angles of impact from 5 to 25 degrees with velocities of 0.2 to 1.2 m/sec (0.5 to 4 ft/sec). An example matrix for velocities and angles for the load beam experiments is shown in Figure F-2.

d. Similar instrumentation used during the prototype experiments was utilized for the full-scale experiments. This included accelerometers (over 12 locations on barge train), strain gages, and clevis pin load cells in the lashing parts. The instrumentation data were collected using over 80 channels of instrumentation on both the barge and lock wall. These experiments also utilized a Differential Global Positioning System on the barge train to measure the velocity, angle, and rotation during impact as well as high-speed cameras to capture the barge-wall and barge-fender interaction. In addition, new instrumentation was developed to measure the actual load normal to the barge and wall. This consisted of a load-measuring beam that had two clevis pin load cells capable of measuring up to 5,388 kN (1,200 kips) of force. In addition, a system of polyvinyl di-flouridene sensors was developed at ERDC as part of a redundant load measurement system on the load beam.

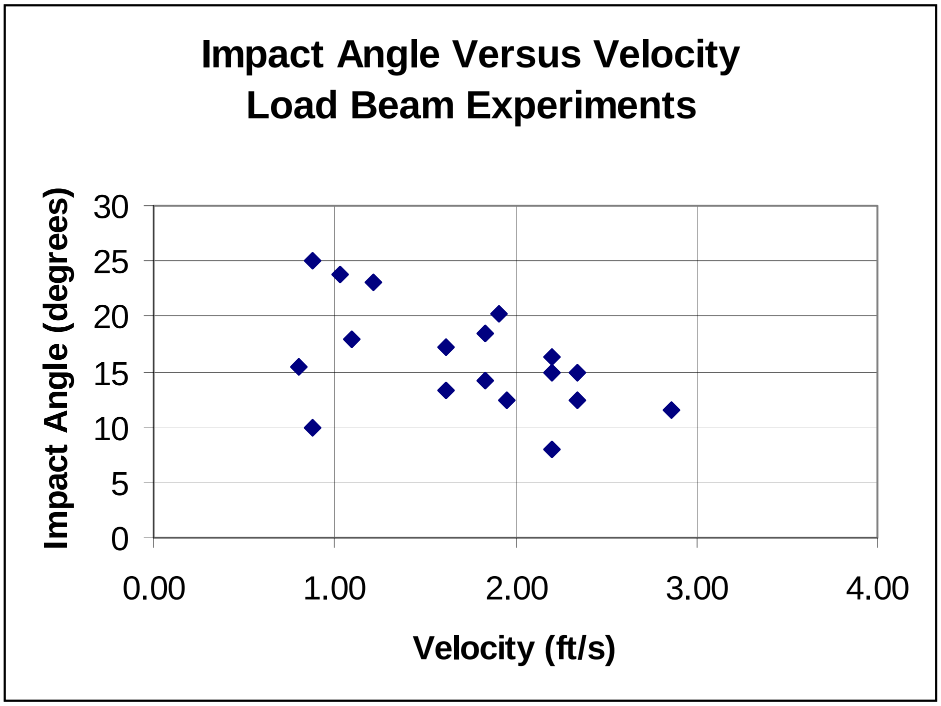

Figure F-2. Impact angle and velocities matrix for load beam experiments

F-4. Full-Scale Crushing Experiments

a. The full-scale crushing experiments were conducted in New Orleans, Louisiana, at the Halter Gulf Repair facilities during 21-23 June 2000. The experiments consisted of using two jumbo open hopper 29- by 41-m (95- by 135-ft) barges that were recently removed from service on the inland waterways and donated for the experiments. The barges were impacted using the 14-MN Statnamic load device owned by Applied Foundation Testing of Green Cove Springs, Florida. The Statnamic device is used primarily to test the axial and lateral capacities of piles and drilled shafts. The Statnamic device used for the experiments has the capability to deliver up to 10,675 kN (2,400 kips) of lateral force at a time duration similar to a barge impact. Figure F-3 shows the Statnamic equipment and the experimental setup during the crushing experiments.

b. A total of nine experiments were conducted on both the barge corners and headlogs (front face of the barge above the rake) of the two barges to determine the impact forces and deformations of the components. The experiments were conducted by incrementally loading the barge first to gain the linear response of the component and second to get the plastic or nonlinear response of the barge system. The barges were instrumented with accelerometers, strain gages, and force load cell to capture the impact data. High-speed and normal-speed video equipment was positioned above the impact zone to document the deformations and movements of the barge during impact. The impact loads on the barges ranged from 1,779 kN (400 kips) up to 7,117 kN (1,600 kips) of lateral forces. Deformations range from no observable to a foot of displacement. Figure F-4 shows the crushing damage to the headlog of the barge under a 3,558-kN (800-kip) force applied between rake trusses. Maximum deformation of the headlog in Figure F-4 is approximately 23 cm (9 in.).

Figure F-3. Statnamic device and experimental setup during experiment (Note: The detonation of the Statnamic device has just occurred at the time of the photograph)

Figure F-4. Crushing damage of barge headlog, Experiment 9

F-5. Summary of Experimental Results.

a. The series of full-scale experiments conducted have been very beneficial in defining the complex behavior of a barge system during impact. These types of measurements have never been quantified before and give a better understanding of how the system works so that future modeling efforts can reflect the actual dynamics of the system.

b. While the data collected from these experiments are extremely valuable, the results do have some limitations before they can be extracted fully toward design. First, the prototype and full-scale experiments were for lower ranges of approach velocities and angles for barge trains on the inland waterway. Therefore, these data should not be extrapolated to high-speed impact events such as a loss of power or control. Second, these experiments were under controlled circumstances and included the preference of the towboat captain to maintain a safe environment during the experiments. This preference does not include any unusual approach conditions due to pilot error, currents, or outdrafts that typically occur at navigation structures. Third, only a limited number of crushing experiments, while designed more for head-on or side impact with structures, was conducted. This data set is only for typical inland waterway barges but cannot directly account for variation of the different barge types in service on the inland waterway.