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Design Concept and Analysis for a Navigation Dam Gate Guard

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PURPOSE: Accidents on navigable waterways in the United States can cause barge tows to break up and, subsequently, individual barges to be carried downstream by the current. As a breakaway barge approaches a navigation structure, its path is essentially determined by the flow patterns around the lock and dam. A primary concern is that a barge will travel to the dam, pass between spillway gate piers, and either strike a gate or become jammed. Either way, the result can be the loss of gate control and perhaps the loss of a navigable pool. Hite (2008) reports on recent closures of U.S. Army Corps of Engineers navigation projects attributed to tow/barge accidents. These accidents have been costly to the towing industry due to closures and to the government due to expensive structural repairs. Examples of accidents that have occurred in the last decade include events on the Ohio River at Belleville Locks and Dam (Figure 1) and at Montgomery Lock and Dam both in January 2005, Smithland Locks and Dam in April 2005, Lock and Dam No. 2 on the Red River in December 2004, and Cheatham Lock and Dam on the Cumberland River in March 2002 (Figure 2).



Figure 1. Barge accident, Belleville Locks and Dam, Ohio River, January 2005.

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Figure 2. Barge accident, Cheatham Lock and Dam, Cumberland River, March 2002.

Removing the barges from the gates can be a difficult, time-consuming, and expensive operation (Hite et al. 2006). Designers and operators of locks and dams need a means of arresting breakaway barges and avoiding their impact on critical structural and mechanical components. A device to protect spillway gates from breakaway barges would be an asset to Corps of Engineers navigation projects.

BARGE IMPACT LOADS: The key to developing a sufficient device to absorb the impact of a runaway barge is accurately determining the loads that the barge will impart during impact. The total load in the direction of impact is comprised of the impact force and the drag force the currents induce on an arrested barge. The impact force is expected to be significantly larger than the drag forces, so the maximum impact force is taken as the design load. Haehnel and Daly (2004) reviewed three approaches that represent the existing guidance for estimating maximum impact forces generated by floating objects. They use a one-degree-of-freedom model to show that the three methods are essentially equivalent. The impact is modeled as a single degree-of-freedom system consisting of the object being impacted and the impacting object. A schematic of this system including the associated stiffnesses and dampers is shown in Figure 3. In this schematic, the stiffness associated with the foundation is k_{found} , the stiffness associated with the deformation of the structure is k_{def} , and the stiffness of the impacting object (in this case the barge) is k_{barge} . The corresponding damping coefficients are denoted as “c”s. Ignoring all damping in the system,

which should be small given the expected magnitude of the impact force and combining the stiffness terms into a system or effective stiffness k_{eff} , the equation of motion for this system is

$$(1 + C_a) m_{barge} \ddot{x} + k_{eff} x = 0 \quad (1)$$

where m_{barge} is the mass of the barge, C_a is the added mass coefficient which typically ranges from 0.10 to 0.15 (e.g. Keuning and Beukelman 1979), k_{eff} is the effective stiffness, x is the displacement, and the dots represent derivatives with respect to time. Following Haehnel and Daly (2004), the displacement response to impact is assumed to be harmonic and if the time at initial contact is $t = 0$, then the displacement is

$$x = u_{barge} \sqrt{\frac{(1 + C_a) m_{barge}}{k_{eff}}} \sin \left[t \sqrt{\frac{k_{eff}}{(1 + C_a) m_{barge}}} \right] \quad (2)$$

where u_{barge} = the barge velocity immediately before impact.

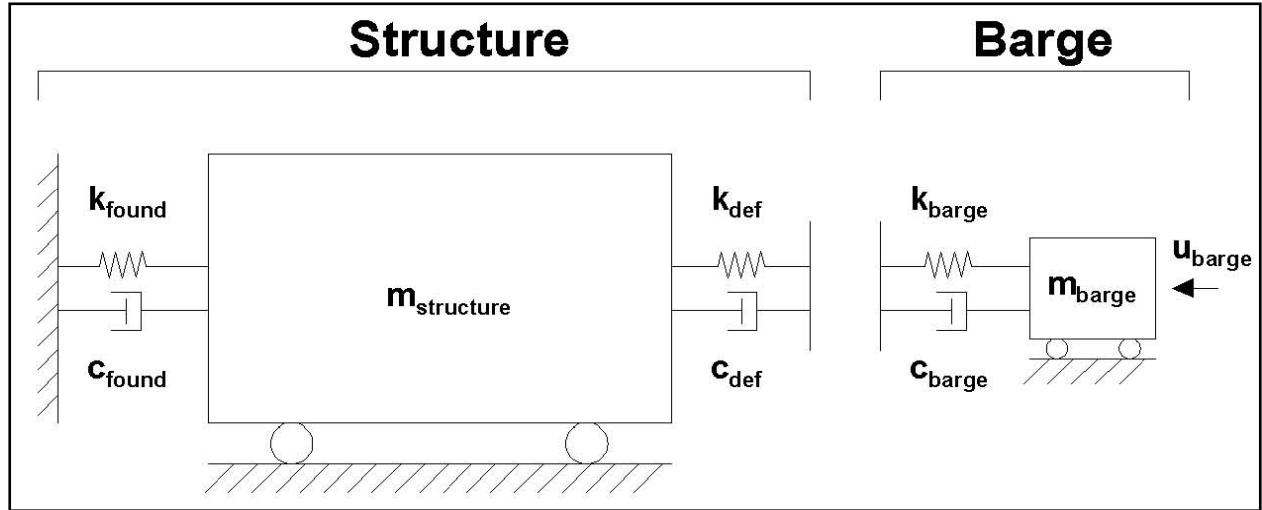


Figure 3. Single degree-of-freedom system of a barge impact.

From an impulse-momentum approach to the problem, the average force (F_{avg}) during a collision is the momentum of the barge immediately before impact divided by the total time of the collision ($t_{collision}$) or

$$F_{avg} = (1 + C_a) \frac{m_{barge} u_{barge}}{t_{collision}} \quad (3)$$

From equation (2), “the functional dependence of force on time is sinusoidal,” so the maximum force (F_{max}) can be calculated by

$$F_{max} = \frac{\pi}{2} F_{avg} = \frac{\pi}{2} (1 + C_a) \frac{m_{barge} u_{barge}}{t_{collision}} \quad (4)$$

Computing the impact force during the collision requires knowledge of the barge's mass and velocity. The barge mass is calculated from the volume of water displaced by the vessel, but the barge velocity is more difficult to attain. As a breakaway barge approaches a structure, it travels with the velocity of flow near the structure. Simulating the flow conditions with a two-dimensional, depth-averaged hydraulic flow solver is an efficient means of determining the flow velocities near the structure. The velocity of a barge floating in this flow field can be estimated as the flow velocities near where the barge impacts the structure. If the impact location is not known, a representative velocity in the vicinity of the structure should be used as the design velocity.

Classical ways of determining the maximum impact loads require knowledge of either the duration of the collision or the deformation distance of the object being impacted. The collision time is dependent on the conditions of an impact such as materials, sizes, velocities, etc. Therefore, empirical data is the key to estimating a reasonable value for the collision time. A method that relates the maximum impact load to the energy of the barge and the stiffness of the impacted structure is currently under development, but is not complete. Such a relation would remove the need for direct knowledge of the collision time or the distance the impacted structure deforms during the collision.

OTHER DESIGN CONSIDERATIONS: The initial focus of the gate guard design was determining how to withstand the barge's impact load, but other factors contributed to the final concept. Rather than requiring an immediate stop, the guard could undergo a controlled deformation as the barge is brought to rest.

To avoid the accumulation of debris or ice, any structure added to a navigation dam could not rest in or on the pool. However, it could be positioned in such a way that allowed rapid deployment. The method of deployment was then considered given the magnitude of barge impact loads and the short warning before collision. Remote deployment, perhaps from the control house of the structure, was considered critical to increase safety of personnel.

Navigation projects that have large pool variations throughout the year require that the structure be positioned for barge impact at lower pools, but not so low that at high water, the barge simply floats over it. Modifications to the concept design will be required for sites having extremely large pool variations. Design details such as overall dimensions and mounting locations will need to be developed on a project-specific basis.

DESIGN CONCEPT: The device (shown in Figure 4) is a set of cables supported by tetrahedra placed on the spillbay piers of a navigation dam. When not deployed (see Figure 5) the tetrahedra sit on top of the piers and have no effect on the flow approaching the spillway gates or the flow near the structure nor will they collect debris. During deployment, the tetrahedra rotate forward until they come to rest on the piers. The device remains in front of the piers until the barges have been captured.

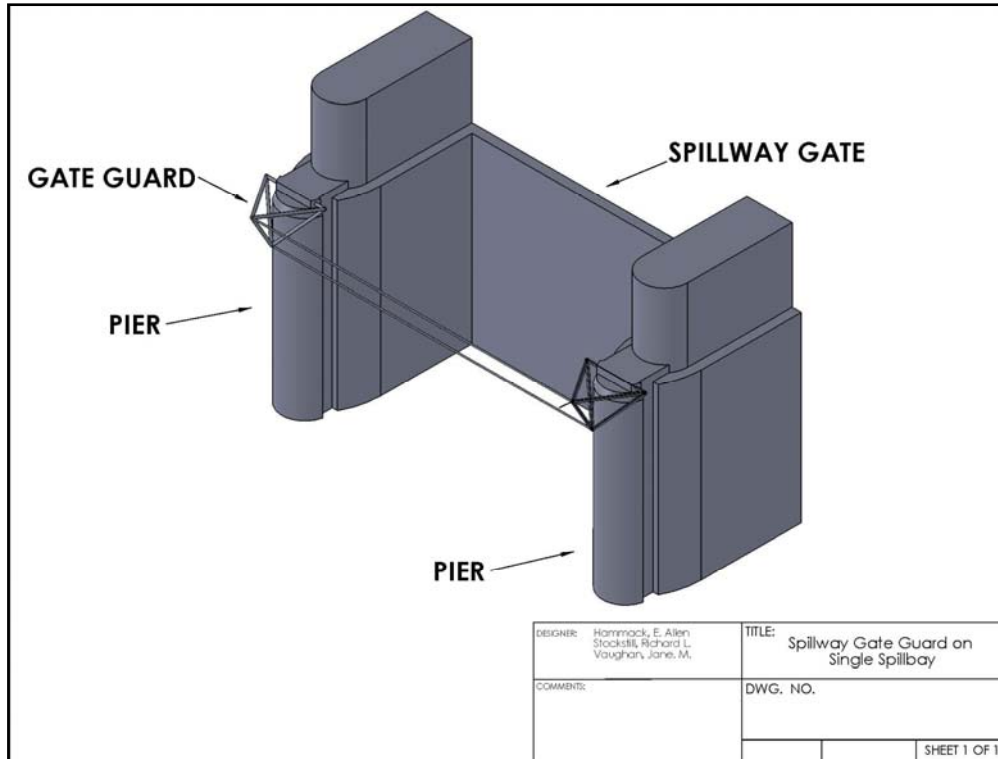


Figure 4. Spillway Gate on a Single Spillbay.

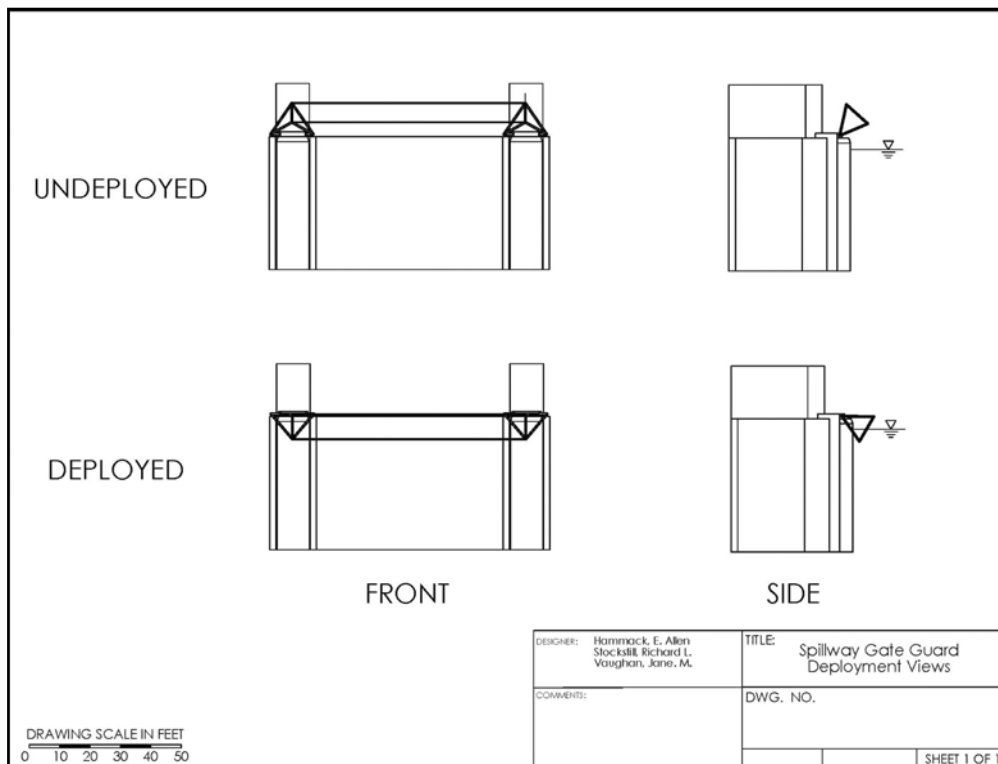


Figure 5. Undeployed and Deployed Configurations of the Spillway Gate Guard.

Two cables connect each adjacent tetrahedron. A vessel floating toward a spillway gate will impact the lower cable initially, which is designed to absorb the majority of the vessel's longitudinal momentum. After impacting the lower cable, the vessel may start sliding over the bottom cable. The likelihood of this behavior is increased if the front of the barge – because of the rake – makes initial contact. If this sliding occurs, the upper cable will limit the vertical movement until the vessel stops. These two cables work in conjunction to catch the vessel as it moves toward the spillway gate. Figure 6 shows the layout of the spillway gate guard.

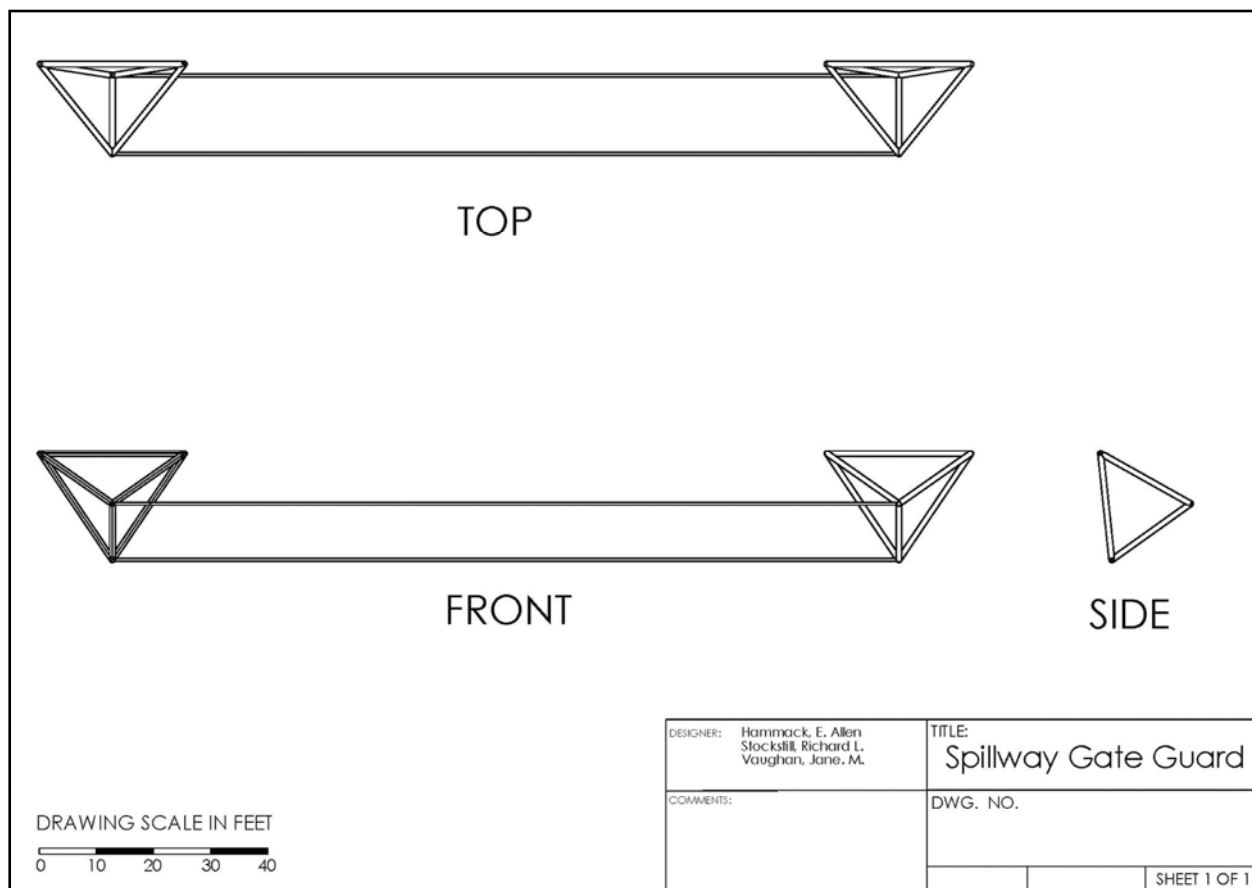


Figure 6. Spillway Gate Guard configuration.

STRUCTURAL ANALYSIS: A structural finite-element analysis was performed to determine the internal loads on each member of the structure as well as its deflection during impact. Truss elements were used to represent each member of the tetrahedra. Each tetrahedron in the device is a space truss with an external load applied at one vertex. The member sitting on the spillbay pier was assumed to be rigid. The barge was assumed to impact a single cable at a single point (its midspan) and not rotate after contact, so that the structure completely absorbed the impact. This impact scenario is shown in Figure 7. The impact force was divided equally between the two closest tetrahedra.

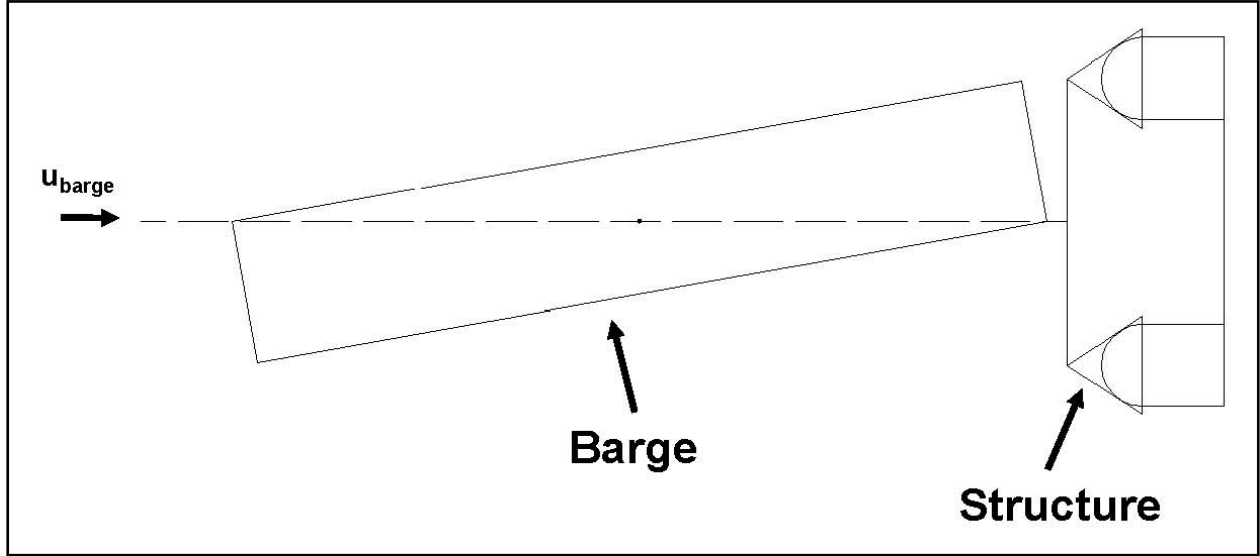


Figure 7. PLAN view of impact scenario used for Spillway Gate Guard sizing for Cheatham Lock and Dam.

The cable must be strong enough to withstand the total impact force of the barge while transferring that load to the tetrahedra. A cable can be chosen such that its rupture strength (a readily-available property) is sufficiently robust to withstand the impact. Assuming equilibrium at maximum impact, a static-analysis using the impact load from the barge was used to determine the tension in the cable (T_{cable}):

$$T_{cable} = \frac{F_{barge}}{2 \sin \theta} \quad (5)$$

where θ is the angle the cable makes with the axis of the dam at the time of maximum cable deflection.

The factor of safety for the cable rupturing is

$$FS_{cable} = \frac{T_{cable}}{T_{rupture}} \quad (6)$$

where $T_{rupture}$ is the maximum force the cable can withstand before rupturing. The analysis used to determine the cable tension does account for stress concentrations at the point of impact. These concentrations could increase the local stresses above those calculated in the outlined gross-load approach. Calculating such concentrations requires a more-detailed (likely finite-element) analysis, which is beyond the scope of this study. In lieu of such analysis, the cable can be sized by assuring that the cable tension is much larger than its rupture load.

The internal forces (F_{member}) for each member of the structure were calculated from the finite-element nodal solution. The axial stresses were calculated for each member.

$$\sigma_{axial} = \frac{F_{member}}{A_{member}} \quad (7)$$

Here, A_{member} is the cross-sectional area of the member.

The factor of safety for the truss members failing in either tension or compression is

$$FS_{axial} = \frac{\sigma_{yield}}{\sigma_{axial}} \quad (8)$$

where σ_{yield} is the yield strength of the truss material.

Each member is a slender, simply-supported column, so the buckling potential was evaluated. The critical buckling force (F_{buckle}) was calculated from the Euler bending formula

$$F_{buckle} = \frac{\pi^2 E_{member} I_{member}}{(K_{eff} L_{member})^2} \quad (9)$$

where

- E_{member} = modulus of elasticity of the tetrahedra member material
- I_{member} = moment of inertia of the tetrahedra member cross-section
- K_{eff} = effective length factor for a member of the tetrahedra
- L_{member} = length of a member of the tetrahedra

For the finite-element analysis, the tetrahedra were treated as space trusses, so the effective length factor is 1.0. If the tetrahedra are analyzed as frames, where the members are not allowed to rotate freely (both ends fixed), an effective length factor of 0.5 should be used.

The factor of safety for the truss members failing in buckling is

$$FS_{buckle} = \frac{F_{buckle}}{F_{member}} \quad (10)$$

One of three methods of failure – cable rupture, axial failure of the truss members, and buckling of the truss members – is considered most likely for a barge impact on the lower cable.

DEMONSTRATION PROJECT: Cheatham Lock and Dam was selected as the demonstration project for developing a concept design. Cheatham Lock and Dam is located on the Cumberland River near Ashland City, TN at river mile 148.7 (42 miles downstream of Nashville, TN). The dam has seven tainter gates, each of which is 60 ft wide by 27 ft tall. The Cheatham project was chosen partly because in 2002 a gate was damaged by a breakaway barge, the gates are as wide as typical Corps navigation dams (50 ft and 60 ft wide gates are most common), the Cumberland River is not extremely wide (resulting in a reasonable flow modeling effort), and the operations personnel were receptive to engaging with the researchers.

FLOW MODEL: A two-dimensional, depth-averaged flow simulation was performed to reproduce the navigation conditions associated with an accident at Cheatham Lock and Dam on March 20, 2002, where eleven barges piled onto the piers and spillway gates and damaged one gate. On that day, the total river discharge was 122,000 cfs with 98,000 cfs passing over the spillway with the gates fully-opened and 24,000 cfs going through the powerhouse. The upper pool was at elevation 386.3 ft.

The Corps of Engineers district office in Nashville, TN, provided the bathymetric information of the forebay and as-built drawings of the structure used to build the computational mesh. The model flow domain extended from the dam upstream 2,100 ft and included the powerhouse trash boom and lock guard wall piers. The mesh, created using the Surface-water Modeling System (SMS) contained 3,700 nodes and 6,900 elements with sides that were between 5 ft and 45 ft long. Information on SMS is available at <http://chl.erdc.usace.army.mil/sms>.

The flow patterns in the approach to Cheatham Lock and Dam are shown in Figure 8. The velocities directly in front of the spillway piers are the specific pieces of information that need to be gleaned from the flow solution. These velocities were about 7 ft/s, and this value was used as the velocity of the vessel when it impacts the gate guard's cable.

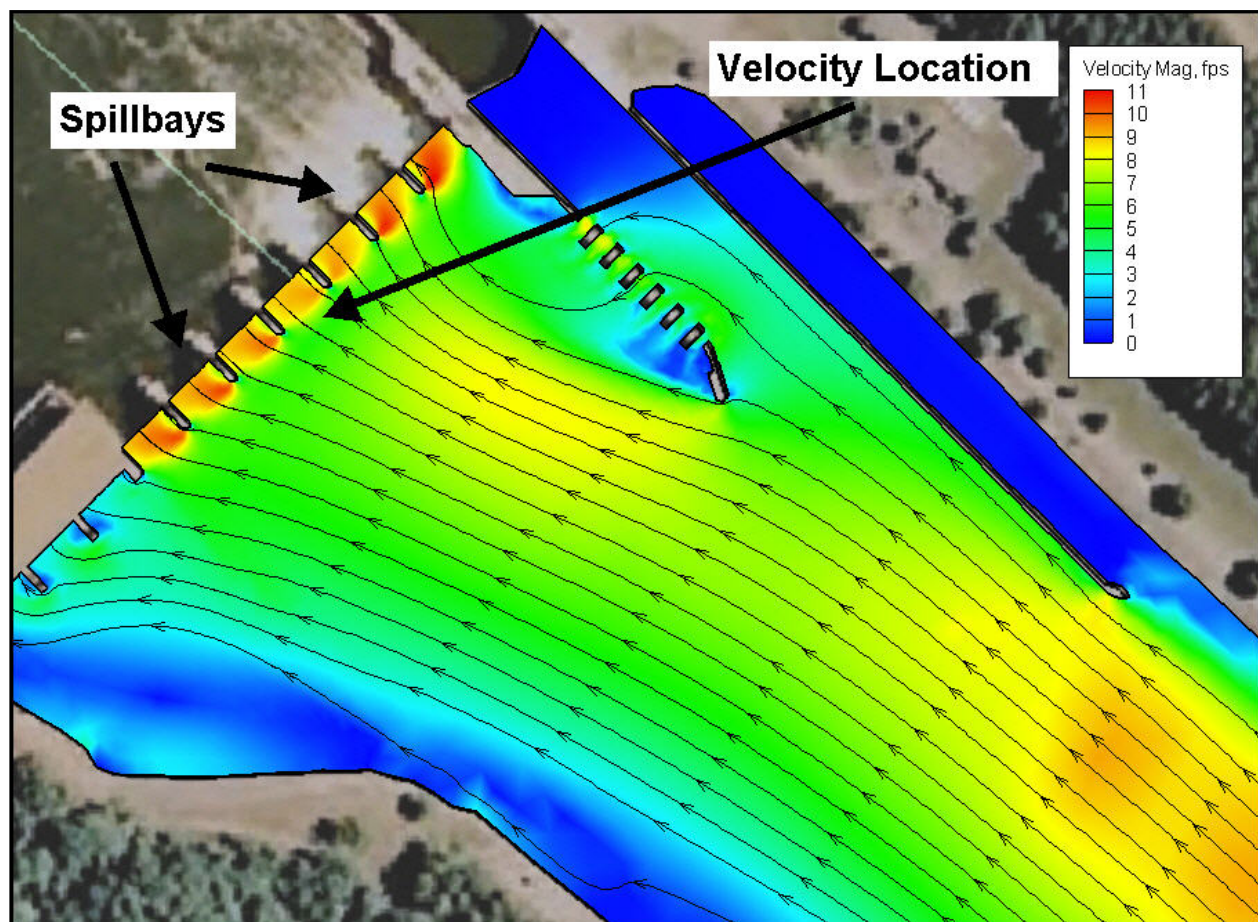


Figure 8. Flow patterns and velocity magnitude contours for 20 March 2002 flow conditions (discharge 122,000 cfs, pool el 386.3 ft).

CONCEPT DESIGN: The gate guard concept design has been sized for Cheatham Lock and Dam using the previously-detailed analysis procedure. The sizing was based on the impact of a single jumbo barge (195 ft by 35 ft) drafted at 9 ft, moving at 7 ft/s striking the lower cable at midspan. A collision time of 3.0 sec, which is representative of the results reported by Martin (1989), was chosen for illustrative purposes. An added mass coefficient of 0.15 was used for this analysis. Applying equation (4) with these quantities, the force of the barge impacting the structure is about 750,000 lb.

The cables spanning the spillbays form a 20° angle with the horizontal axis of the spillway. Each cable is composed of 150 commercially-available strands of steel cable. From equation (5), the tension in each cable at maximum impact is about 1.1 million lb; this load was used as the force boundary condition in the finite-element analysis of the structure. The trusses are comprised of cylindrical steel members. Table 1 lists the sizes of the cable, the sizes of the truss members, and the properties for the material used for the cable and truss members. Table 2 summarizes the results of the structural analysis.

Table 1. Gate Guard Dimensions and Material Properties	
Cable Strand Diameter (ft)	0.083
Total Cable Diameter (ft)	0.5
Cable Length (ft)	62
Truss Member Diameter (ft)	1.5
Truss Member Lengths (ft)	18.0 16.7 (2) 14.7 (2) 13.6
Modulus of Elasticity (ksi)	27,600
Yield Strength (ksi)	53,100
Rupture Strength, Cable (kip)	14.4

Table 2. Gate Guard Structural Analysis Results	
Maximum Member Force (kip), Tension	830
Maximum Member Force (kip), Compression	830
Maximum Nodal Deflection (ft)	0.003
Factor of Safety for the Cable, Rupture	2
Factor of Safety for the Truss Members, Tension/Compression	16
Factor of Safety for the Truss Members, Buckling	54

With the given impact load and location, the structure deflects much less than an inch. If the gate guard is intended to be less rigid during impact, then the truss members should be modified in a way to lower the effective stiffness of the entire truss. If such modifications are made, though, the factors of safety for all three modes of failure included in this technical note must be monitored closely, because the buckling force in particular is very sensitive to the truss member geometry. However, the cable is much more likely to rupture with the current geometry than the truss members. The impact force and factor of safety calculations are shown in Figure 9.

Barge Impact Force:

$$m_{\text{barge}} = \rho_{\text{water}} L_{\text{barge}} W_{\text{barge}} d_{\text{barge}} = \left(1.94 \frac{\text{slug}}{\text{ft}^3} \right) (195 \text{ ft}) (35 \text{ ft}) (9 \text{ ft}) = 118,980 \text{ lb}$$

$$F_{\text{max}} = \frac{\pi}{2} (1 + C_a) \frac{m_{\text{barge}} u_{\text{barge}}}{t_{\text{collision}}} = \frac{\pi}{2} (1 + 0.15) \frac{(118,980 \text{ lb}) (7 \text{ ft/s})}{3 \text{ s}} = 752,247 \text{ lb}$$

Factor of Safety – Cable Rupture

$$T_{\text{cable}} = \frac{F_{\text{barge}}}{2 \sin \theta} = \frac{752,247 \text{ lb}}{2 \sin (20.4^\circ)} = 1,080,861 \text{ lb}$$

$$FS_{\text{cable}} = \frac{T_{\text{cable}}}{T_{\text{rupture}}} = \frac{2,160,000 \text{ lb}}{1,080,861 \text{ lb}} = 1.998$$

Factor of Safety – Axial (Using the Maximum Member Force)

$$A_{\text{member}} = \frac{\pi}{4} d_{\text{member}}^2 = \frac{\pi}{4} (1.5 \text{ ft})^2 = 1.767 \text{ ft}^2$$

$$\sigma_{\text{axial}} = \frac{F_{\text{member}}}{A_{\text{member}}} = \frac{829,275 \text{ lb}}{1.767 \text{ ft}^2} = 469,273 \text{ psf}$$

$$FS_{\text{axial}} = \frac{\sigma_{\text{yield}}}{\sigma_{\text{axial}}} = \frac{7,644,069 \text{ psf}}{469,273 \text{ psf}} = 16.3$$

Factor of Safety – Buckling (Using the Maximum Member Force)

$$I_{\text{member}} = \frac{\pi}{64} d_{\text{member}}^4 = 0.249 \text{ ft}^4$$

$$F_{\text{buckle}} = \frac{\pi^2 E_{\text{member}} I_{\text{member}}}{(K_{\text{eff}} L_{\text{member}})^2} = \frac{\pi^2 (3,968,232,504 \text{ psf}) (0.249 \text{ ft}^4)}{[(1)(14.7 \text{ ft})]^2} = 44,850,992 \text{ lb}$$

$$FS_{\text{buckle}} = \frac{F_{\text{buckle}}}{F_{\text{member}}} = \frac{44,850,992 \text{ lb}}{829,275 \text{ lb}} = 54.1$$

Figure 9. Sample calculations used in the application of the spillway gate guard at Cheatham Lock and Dam.

ADDITIONAL INFORMATION: This CHETN is a product of the Barge Boom Work Unit of the Navigation Safety Research Program being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to Allen Hammack (601-634-3628; e-mail: Allen.Hammack@usace.army.mil) or Dr. Richard L. Stockstill (601-634-4251; e-mail: Richard.L.Stockstil@usace.army.mil). This technical note should be cited as follows:

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