Assessment of Bridge Vulnerability to Hydraulic Failures

A. M. Shirolé and M. J. Loftus

A comprehensive Bridge Safety Assurance (BSA) program is being implemented in New York State. It provides a system to identify, assess, and evaluate the vulnerability of bridges to catastrophic failures and then implement actions to eliminate or mitigate such vulnerabilities. On the basis of a national survey of bridge failures, six failure modes were identified as being the most significant in terms of the potential damage they can cause to highway bridges in New York State: hydraulic, overload, steel structural details, collision, concrete structural details, and earthquake. The assessment phase of the overall BSA program as it relates to the hydraulic failure mode is described. Specific details of screening, classifying, and rating steps are described, and the current status of these assessment efforts in New York State is presented. Vulnerability-reduction actions that have been implemented as a result of the assessment process to ensure bridge safety against hydraulic failures are described as well.

The New York State Department of Transportation's (NYSDOT's) Bridge Safety Assurance (BSA) program provides a systematic method to reduce vulnerability of the state's bridges to all potentially significant modes of failure. The program has four phases:

- Identification of significant modes of failure,
- Assessment of vulnerability of bridges to failure modes,
- Evaluation of vulnerable bridges, and
- Implementation of recommendations to reduce vulnerability.

Planning aspects of these four phases have been described previously by Shirolé and Holt (*1*). The identification phase has been completed, and the following six failure modes were identified as the most significant in terms of the potential damage they can cause to highway bridges in New York State:

- Hydraulic,
- Overload,
- Steel structural details,
- Collision,
- Concrete structural details, and
- Earthquake.

The failure modes were identified on the basis of the results of a survey on bridge failures since 1950 compiled by NYSDOT.

The evaluation and implementation phases are basically similar for all the identified modes of failure. These phases are described elsewhere (*1*) and will not be discussed here.

New York State Department of Transportation, 1220 Washington Avenue, State Office Campus, Building 5, Albany, N.Y. 12232.

This paper is focused on the assessment phase of the BSA program as it relates to hydraulic vulnerability. Specific details of the assessment process and some vulnerability reduction actions that have been implemented to ensure bridge safety are described.

PROCEDURES FOR HYDRAULIC ASSESSMENT

The objective of the hydraulic assessment phase of the BSA program is to rate the state's bridges according to their relative vulnerability to hydraulic failure. This objective is accomplished through a series of screening, classifying, and rating steps that review hydraulic characteristics of individual bridges to group them according to their relative susceptibility, and classify and rate them on a list for appropriate actions.

Figure 1 is a flowchart of the overall hydraulic vulnerability assessment phase. Key elements in the process are the screen, classify, and rate steps. Each is designed to provide an increasing understanding of the bridge's hydraulic vulnerability. They are intended to be progressed sequentially on a priority basis. Bridges with higher vulnerabilities are moved through the subsequent steps first to focus assessment and corrective activities on the most critical bridges in the shortest time. This results in a staggered progression of bridges through the assessment process.

Vulnerability reduction measures shown in Figure 1 consist of actions based on findings of the screening, classifying, and rating steps. They include establishing floodwatch and post-flood inspection lists, and identifying bridges requiring immediate or future scour-protection retrofit.

The procedures used in the screening and classifying phases of the assessment process are based in part on recommendations made by a special Bridge Safety Assurance Task Force (BSATF), appointed to study bridge safety assurance measures in New York State. It was made up of nationally recognized experts in a variety of fields, including hydraulics. Richardson and Huber (*2*) reported on BSATF recommendations relating to hydraulics. For implementation purposes, task force recommendations were modified to better fit conditions in New York. In general, the modifications did not affect specific vulnerability factors being used, but consisted of changes in the logic used in the screening or classifying processes or adjustments in the importance or weight assigned to vulnerability factors. For example, the classification step uses only the most critical substructure unit as the basis of final evaluation results, whereas the task force process used a combination of pier and abutment evaluations. In New York there is concern over hydraulic vulnerability of single-span

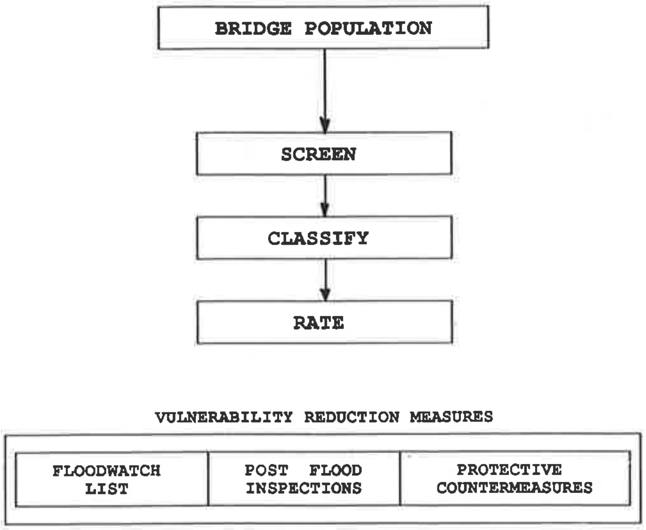

FIGURE 1 Hydraulic vulnerability assessment process.

bridges, and the task force procedures made it unlikely that a bridge without piers would be evaluated as highly vulnerable. Another example of an area that changed is the weights used for different types of pier and abutment foundation configurations. These weights were adjusted to provide a greater distinction between configurations of different vulnerabilities.

The assessment procedures described here are not being used to assess vulnerability of bridges on Long Island and in the New York City area. Bridges in those areas are subject to hydraulic forces (e.g., tidal) that differ from the forces in the other areas of the state. Consequently, different methods are required to assess vulnerability. Procedures to assess the vulnerability of bridges in those areas are being developed.

Descriptions of the different steps in the vulnerability assessment process follow.

Screen

Figure 2 is a flowchart of the screening process. The primary goal of the screening step is to set priorities for progressing bridges to the classifying step. This goal is accomplished through a preliminary inventory data base screen and a more refined susceptibility screen. As a result of these screens, bridges are put into four susceptibility groups, which rank the order for progressing to the classifying step.

The inventory screen is designed to evaluate a large population of bridges, using information contained in Bridge Inventory and Inspection System (BIIS) data files. Structures not over water are identified and removed from the assessment process. No further actions are required for them. The remaining bridges are screened on the basis of key substructure, superstructure, and hydraulic information in the BIIS data base. This screening provides a relative assessment of hydraulic susceptibility of a bridge and is used to set the order for progressing bridges to the susceptibility screening step.

As seen in Figure 2, the susceptibility screening process is divided in two parts (*3*). This process uses a review of bridge plans, construction documents, inspection reports, and any other available information to place bridges in four susceptibility groups, which imply a relative susceptibility to damage from hydraulic forces and determine the order in which they are progressed to the classifying step.

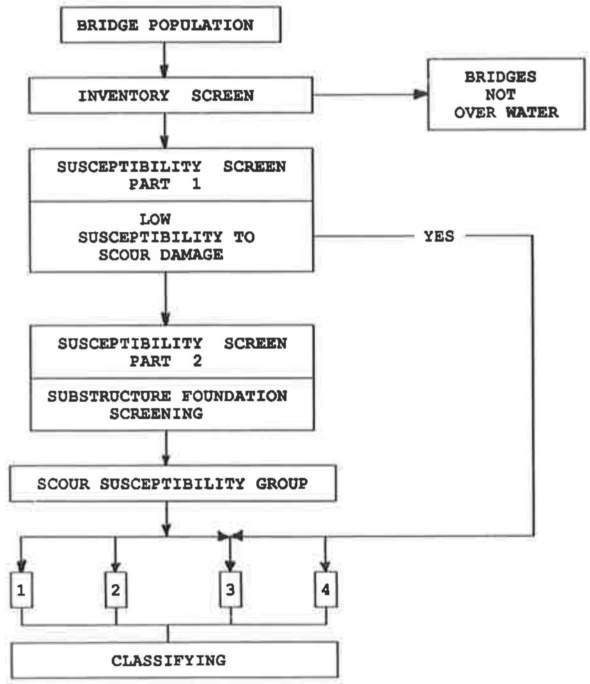

FIGURE 2 Hydraulic vulnerability assessment screening process.

In the first part of the susceptibility screening, structures having a low susceptibility to scour damage are identified on the basis of the following screening criteria:

- Piers and abutments out of floodplain,
- Slow stream velocity,
- Nonscourable foundation materials, and
- Culverts.

Structures meeting any one of these criteria are placed in the third or fourth susceptibility group. Bridges not meeting these criteria are progressed to the second part of the susceptibility screening step. The actual group selected depends on whether any indications of scour damage are noted in the inspection and condition reports. If scour damage is indicated, the structures are placed in the higher susceptibility group. For example, bridges with piers and abutments founded on sound nonscourable rock foundations are identified and placed in the fourth group, provided that there are no indications of scour damage. If there are, then the third group would be appropriate.

In the second part of screening, bridges are placed in the first, second, or third susceptibility group on the basis of pier and abutment foundation configurations and assessment of scour conditions. Figure 3 shows screening criteria and recommended susceptibility groupings. Again, as in the first part of the screen, if there is scour damage, a higher susceptibility group is recommended. For example, a bridge with vertical wall abutments on short piles goes into the second susceptibility group unless it shows scour damage, in which case the first group is recommended.

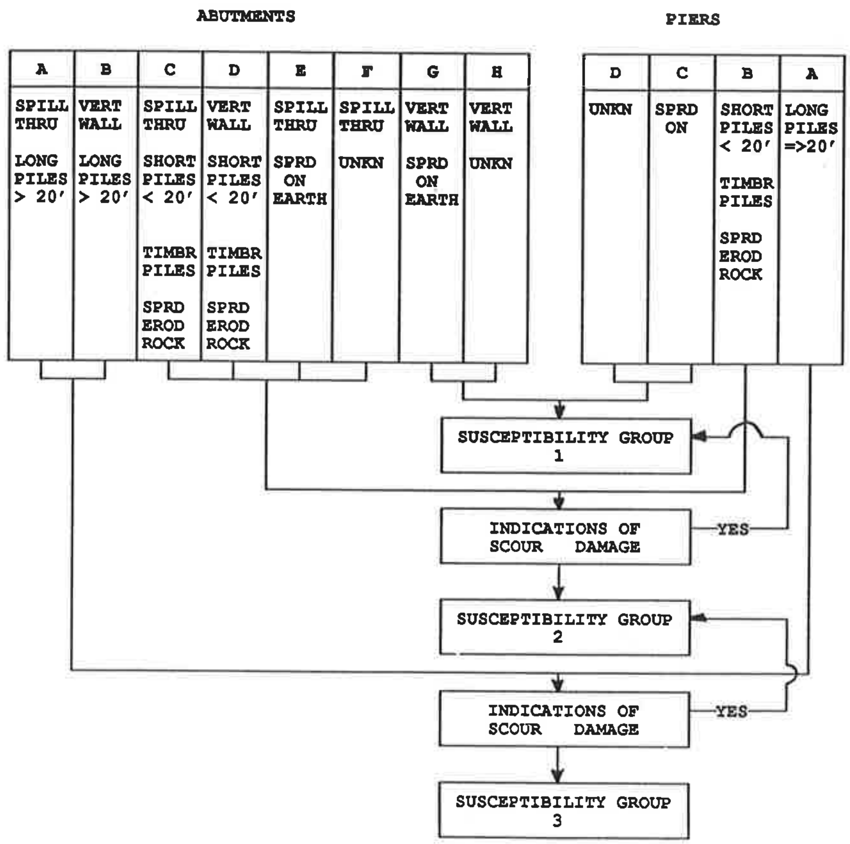

FIGURE 3 Substructure foundation screening.

After susceptibility screening, bridges in susceptibility Group 1 progress to the classifying step, followed by bridges in Groups 2, 3, and 4, respectively.

Classifying

The purpose of the classifying step is to evaluate the vulnerability of a structure to scour damage on the basis of its geologic, hydraulic, and riverine conditions. The product of this step is a classification score that serves two purposes. First, it quantifies potential vulnerability of a structure to hydraulic damage relative to other bridges in the classification process. Second, it places a structure in a high, medium, or low hydraulic vulnerability class.

The vulnerability classes describe the potential of a structure for failure due to scour or other hydraulic forces relative to other bridges in the classifying process. The classes are used in determining vulnerability rating for a structure and also in deciding whether a structure should be placed on a floodwatch list (*4*) or a postflood inspection list.

Field evaluation of the bridge is essential to complete the classifying step. In addition, it is important that classification procedures are performed by an engineer specially trained in bridge hydraulic principles, as these require judgments to be made about hydraulic characteristics of a bridge and its stream.

The high, medium, and low hydraulic vulnerability classes are defined in the following paragraphs.

High Vulnerability Class

For a structure to be placed in the high vulnerability class, conditions must exist on the structure or in the stream that create an unacceptable potential for failure due to scour or other hydraulic forces. "Unacceptable" implies a risk clearly greater than is consistent with design practice, and a single intermediate or large flood could result in a failure. These bridges would be candidates for scour retrofit on a priority basis or on a short-term programmed basis and would have highest priority for detailed hydraulic analysis. Until action is taken and the bridge can be placed in a lower vulnerability class, bridges should be on the floodwatch list. These bridges would also be considered for a postflood inspection list.

Medium Vulnerability Class

For a structure to be placed in the medium vulnerability class, conditions must exist on the structure or in the stream creating a recognizable potential for failure due to flooding. Risk of failure due to a single design flood or a historic flood is slight, but repetitive floods of these magnitudes will probably result in failure. These structures would be candidates for scour-protection retrofit on a programmed basis. A detailed hydraulic analysis is required for these structures, and inclusion on the floodwatch list should be considered. Bridges in this category may also be candidates for a postflood inspection list.

Low Vulnerability Class

For a structure to be placed in the low vulnerability class, conditions must exist on the structure or in the stream presenting little potential for failure due to flooding. There is no risk of failure due to a single design or historical flood, and only a remote chance of failure due to an extreme flood. Scour-protection retrofit is not required for bridges in this category, but scour conditions should be checked as part of general bridge inspections and after major floods. These structures should receive the lowest priority for a hydraulic analysis and need not be placed on the floodwatch list. Inclusion on a postflood inspection list may be considered for some structures in this category.

Figure 4 outlines the classification process, which is composed of two sections: general hydraulic assessment and foundation assessment. The foundation assessment section includes separate evaluations for abutments and piers. Figure 4 also shows the classifying score ranges used to determine vulnerability class for a structure. The ranges are overlapped to allow the evaluating engineer some discretion in assigning a vulnerability class.

In each section of the classifying process, several parameters are examined and a specified value assigned that describes existing conditions, with more vulnerable conditions receiving higher values. Figure 5 shows criteria and classification scores which are used in the general hydraulic assessment process, and Figures 6 and 7 show the criteria and the scores for the abutment and pier foundation assessment processes, respectively. Specific instructions on applying these criteria are in the *NYSDOT Hydraulic Vulnerability Assessment Manual* (*3*).

In the foundation assessment section all abutments and piers on a structure are evaluated, but only the most critical

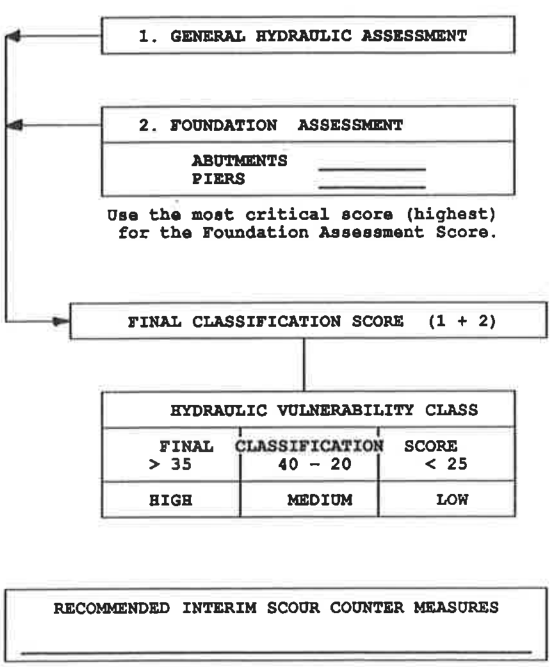

FIGURE 4 Classification process.

a. RIVER SLOPE / VELOCITY		
FLAT 0	MEDIUM 1	STEEP 2-3

b. CHANNEL BOTTOM		
AGGRADING 0	STABLE 1	DEGRADING 2-4

c. CHANNEL CONFIGURATION		
STRAIGHT 0	BRAIDED 1	MEANDERING 2

d. DEBRIS / ICE PROBLEM		
NONE 0	MINOR 1-2	MAJOR 3-4

e. NEAR RIVER CONFLUENCE	
NO 0	YES 1

f. AFFECTED BY BACKWATER	
YES 0	NO 1

g. EXISTING / HISTORIC SCOUR DEPTH			
NONE 0	SMALL (<1') 1	MEDIUM (1-3') 2-3	LARGE (>3') 4-5

h. HISTORIC MAXIMUM FLOOD DEPTH	
< 10' 1	> 10' 2

i. ADEQUATE OPENING	
YES 0	NO 2

j. OVERFLOW RELIEF AVAILABLE	
YES 0	NO 1

FIGURE 5 General hydraulic assessment criteria.

substructure unit is used to determine the foundation assessment score.

The final classification score for a structure is determined by adding scores from the general hydraulics assessment process and the foundation assessment process. The highest score represents the most vulnerable structure. Classification scores are then used to determine appropriate vulnerability classes based on the ranges shown in Figure 4.

Classification procedures are designed to ensure objectivity and provide a degree of uniformity in evaluations, yet allow for the judgment of a trained hydraulic engineer. The process allows for engineering judgment in assessing observed conditions and accounting for factors pertinent but possibly not covered in the detailed procedures. Evaluators have the option of increasing or decreasing scores, and can use some judgment in deciding the final vulnerability category for a structure.

An ancillary function of the classifying step is to identify any bridges exhibiting potentially catastrophic conditions that require immediate scour-protection countermeasures to safe-

a. EXISTING SCOUR COUNTERMEASURES					
NOT REQ'D	SHEET PILE WALL	COFFERDAM	RIPRAP	OTHER	NONE
0	0	0	1	1	5

b. ABUTMENT FOUNDATION								
A	B	C	D	E	F	G	H	I
SPILL THROUGH				VERTICAL WALL				
LONG PILES >20' NON-EROD ROCK	SHORT PILES <20' TIMBR EROD ROCK	SPRD ON EARTH	UNKN	LONG PILES >20' NON-EROD ROCK	LONG TIMBR PILES >20'	SHORT PILES <20' EROD ROCK	SPRD ON EARTH	UNKN
0	2	3	3	0	3	5	10	10

c. ABUTMENT LOCATION ON RIVER BEND		
INSIDE	STRAIGHT	OUTSIDE
0	0	1

d. ANGLE OF EMBANKMENT INCLINATION			
0-19	20-44	45-90	>90
0	1	2	4

e. EMBANKMENT ENCROACHMENT		
SMALL	MEDIUM	LARGE
0	2	4

FIGURE 6 Foundation assessment criteria (abutments).

a. EXISTING SCOUR COUNTERMEASURES					
NOT REQ'D	SHEET PILE WALL	COFFERDAM	RIPRAP	OTHER	NONE
0	0	0	1	1	5

b. PIER FOUNDATIONS					
A	B	C	D	E	F
PILES STEEL CONC	SPRD ON NON-EROD ROCK	PILES TIMBR	SPRD ON EROD ROCK	SPRD ON EARTH	UNKN
0	0	4	5	10	10

c. FOOTING / PILE BOTTOM BELOW STREAMBED					
> 20	15-20	10-15	7-10	4-7	< 4
0	1	2	3	4	5

d. ANGLE OF ATTACK (DEGREES)			
0	0-20	20-45	45-90
0	2	3	4

e. PIER WIDTH				
< 3	3-5	5-8	8-10	> 10
1	2	3	4	5

f. SIMPLE SPANS	
NO	YES
0	1

g. MULTIPLE PIERS IN FLOODPLAIN	
NO	YES
0	2

FIGURE 7 Foundation assessment criteria (piers).

guard against failure. If potentially catastrophic conditions are observed, then interim fixes can be implemented until more permanent remedial measures can be designed and constructed. Typically, these interim fixes consist of heavy stone fill placed around abutments and piers.

Rating

The purpose of the vulnerability rating step is to provide a uniform measure of a structure's vulnerability to failure on the basis of likelihood of occurrence and consequences of a failure. Six vulnerability rating categories have been established, common to all six BSA failure modes, allowing comparison among bridges vulnerable to different failure modes.

Definitions for the six vulnerability rating categories are presented in the following list. These categories specify the type of corrective actions needed and the urgency with which these actions should be implemented. They were developed to apply to the modes of failure listed previously.

1. Safety priority action. This rating designates vulnerability to failure resulting from loads or events that are likely to occur. Remedial work to reduce the vulnerability must be given immediate priority, and completion of work is desired within 18 months.
2. Safety program action. This rating designates vulnerability to failure resulting from loads or events that may occur. Remedial work to reduce the vulnerability is desired within 3 years.
3. Capital program action. This rating designates vulnerability to failure resulting from extreme loads or events that are possible but not likely. This risk can be tolerated until a normal capital construction project can be implemented. Remedial work to reduce the vulnerability is desired within 5 years.
4. Inspection program action. Possible but unlikely expectation of a failure that could cause traffic disruptions. Inspection monitoring desired to ensure adequate load resistance.
5. Not vulnerable. Adequate structural resistance to this type of vulnerability. Failure unlikely.
6. Not applicable. No exposure to this type of failure vulnerability.

A vulnerability rating for a bridge is determined in a manner similar to the classification process, where scores are assigned to evaluate parameters for the likelihood and consequences of a failure. These scores are combined and a range of values used to determine the appropriate vulnerability rating category.

The likelihood of a failure occurring is evaluated using results of the classification process and, when available, results of a detailed hydraulic analysis. This ensures that all known information about a structure's vulnerability and resistance to it are included in the rating process.

Consequences of failure are determined on the basis of the type of failure to which a structure is prone, and includes factors to account for the traffic volume and highway classification of the structure.

STATUS OF THE ASSESSMENT PHASE

The hydraulic vulnerability assessment process is currently being implemented for state-owned bridges over water. Advice is being provided for locally owned structures. At this time, state-owned bridges on Long Island and in the New York City area also are not included, as was mentioned previously. The current program encompasses more than 95 percent of the entire state bridge population over water.

The status of the vulnerability assessment program as of July 1991 is presented in the following list. To date, more than 99 percent of bridges included in the program have been screened and more than 40 percent classified. Rating tasks have not yet begun. It is estimated that all state bridges over water will have been screened, classified, and rated by the end of 1993.

- Number of state-owned bridges: 6,625;
- Number of bridges over water: 3,919;
- Susceptibility screening
  - –Group 1: 1,163,
  - –Group 2: 684,
  - –Group 3: 1,022,
  - –Group 4: 1,003,
  - –Total screened: 3,872;
- Classifying
  - –High vulnerability: 141,
  - –Medium vulnerability: 675,
  - –Low vulnerability: 843,
  - –Total classified: 1,659.

In addition to vulnerability assessment steps, the hydraulic vulnerability assessment process also includes continuing strategies to provide protection against hydraulic failures. These strategies include a floodwatch program and postflood inspection program to provide monitoring of vulnerable bridges during and after floods.

Floodwatch Program

The floodwatch program was established with issuance of the *NYSDOT Bridge Flood Warning Action Plan* (*4*). Its purpose is to ensure that bridges with a high susceptibility to damage or failure from hydraulic forces are monitored during periods of flooding for as long as they remain vulnerable. It calls for continual or periodic monitoring of bridges during periods of flood warning as issued by the National Weather Service (NWS). Personnel are placed at a bridge site for the duration of the flood warning event. If any movement, damage, or potentially dangerous conditions are observed, appropriate action, such as bridge closure, can be taken.

Continuous monitoring is provided for bridges having a potential for sudden and catastrophic collapse due to the force of flood waters or other hydraulic forces. These are placed in a high-risk floodwatch category. Bridges less prone to sudden collapse but to more gradual settlement or sagging failure receive intermittent monitoring during a flood. These are placed in a non-high-risk floodwatch category. Both the superstructure type and foundation type are considered in judging potential for collapse.

Criteria for selecting the bridges to be placed on the floodwatch list are based on results of the vulnerability assessment procedures, with more precise criteria applying after each step in the assessment process.

Currently, 703 bridges are included in the New York State floodwatch program.

Postflood Inspection Program

The purpose of this program is to monitor performance of vulnerable bridges after major floods. Bridges over water having a pier or abutment protected with riprap, stone fill, or paving blocks are included on the postflood inspection list. Bridges in the floodwatch program are also placed on the list.

Inspections are conducted following issuance of a flood warning by the NWS, after flood waters have receded enough to allow substructures to be inspected. Only the structures in areas included in the flood warning need to be inspected.

The inspection consists of visual inspection of substructures and protective countermeasures on the bridge. If any movement, loss of material, or any type of damage is observed, the conditions are documented and appropriate corrective actions implemented.

CONCLUSION

The hydraulic vulnerability assessment process described here provides a systematic method for determining hydraulic vulnerability of a large population of bridges. Through a series of screening, classifying, and rating steps, the hydraulic characteristics of bridges are examined, and prioritized lists are developed for corrective action. Concepts included in the assessment process have been developed with substantial input from numerous expert sources, and implementation of these procedures as part of the overall BSA program will significantly lower the vulnerability of New York's bridges to hydraulic failures.

Currently, only state-owned bridges over water are being addressed through the hydraulic assessment procedures. To date, more than 99 percent of these bridges have been screened and more than 40 percent classified. It is estimated that all screening, classifying, and rating efforts for state bridges will be completed by the end of 1993.

REFERENCES

1. A. M. Shirolé and R. C. Holt. Planning For A Comprehensive Bridge Safety Assurance Program. In *Transportation Research Record 1290,* Vol. 1, TRB, National Research Council, Washington, D.C., 1991, pp. 39–50.
2. E. V. Richardson and F. W. Huber. Evaluation of Bridge Vulnerability to Hydraulic Forces, Stream Instability, and Scour. In *Transportation Research Record 1290,* Vol. 1, TRB, National Research Council, Washington, D.C., 1991, pp. 25–39.
3. *NYSDOT Hydraulic Vulnerability Assessment Manual.* Structures Design and Construction Division, New York State Department of Transportation, Albany, Dec. 1991.
4. *NYSDOT Bridge Flood Warning Action Plan For State Bridges.* Structures Design and Construction Division, New York State Department of Transportation, May 1989.

Publication of this paper sponsored by Committee on Structures Maintenance and Management.