# Planning for a Comprehensive Bridge Safety Assurance Program

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With the increasing number of structurally deficient and functionally obsolete bridges and recent catastrophic bridge failures in the United States, the need to strengthen bridge safety has become pronounced. **This paper presents** considerations in planning a comprehensive bridge safety assurance progam, including identification of potential causes and modes of bridge failures based on review of failures, imminent failures and actual closures. As these causes and modes of failure are identified, they are prioritized in terms of their potential impact on the structures for which an agency is responsible. **The paper discusses** steps to develop a rating system that categorizes and ranks bridges by their relative vulnerability to the various failure modes. **Further, it presents** a method of preparing initial screening lists based on characteristics of the site and structure, verifying such lists, and then categorizing them according to appropriate action-needed categories. Preparation of short and long-term strategies to reduce or eliminate vulnerability of bridge failures is also discussed.

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## INTRODUCTION

Since the catastrophic bridge collapse at Point Pleasant, W.V., in 1967, most agencies responsible for bridges have initiated systematic inspection and inventory programs. These were later followed by structural capacity rating and load posting programs as well as improved maintenance practices. Failure of Connecticut's Mianus River Bridge in 1983, the New York State Thruway Bridge over Schoharie Creek in 1987, and that of the US 51 Bridge in Covington, Tennessee, in 1989, have further underscored the importance of inspection, evaluation and maintenance in achieving bridge safety. Bridge engineers have responded to these failures by initiating upgrades of pin and hanger, fracture critical, and scour susceptible structures. These and other efforts have been on a piece-meal basis, in a reactive manner, rather than as a well planned and coordinated proactive strategy. Thus, a strong need exists for agencies responsible for bridges to undertake a systematic program to deal with their vulnerability to all potential modes of failure. A well-planned comprehensive Bridge Safety Assurance (BSA) Program will provide a system to identify, assess, and evaluate vulnerable bridges and then implement actions to prevent these failures.

This paper presents the necessary steps to planning a comprehensive Bridge Safety Assurance program that will facilitate a systematic assessment. It reviews current practices relating to safety assurance and discusses the identification and rating of vulnerability to significant failure modes on the basis of relevant site and structure characteristics. Further, it discusses prioritization of vulnerability reduction needs and formulation of effective strategies to eliminate or reduce failure vulnerabilities of bridges to accomplish short- and long-term objectives.

## REVIEW OF CURRENT PRACTICES

Traditionally, bridge safety assurance practices start by complying with design and material standards to assure safe and durable structures. This is followed by construction inspection to assure compliance with the plans and specifications. Bridge conditions are rated and monitored during biennial inspections while the safe load carrying capacity is assured by the load rating and posting programs. Structure deficiencies identified by these programs are addressed through maintenance, rehabilitation and replacement programs. All of these activities, however, are reactions to observed conditions and do not go far enough. This is because most existing structures were not designed in anticipation of the significantly different but more realistic present day design loads and an improved understanding of environmental conditions. Certain design specification requirements and material characteristics once accepted as "state-of-the-art" have been demonstrated with time and further study to be undesirable and ill-advised. Because of previously unexpected loads and implications of environmental conditions, some of these structures have an inherent vulnerability to certain failure modes. Failures of older bridges due to earthquakes or floods demonstrate this vulnerability.

## SURVEY OF BRIDGE FAILURES

There does not appear to be a central data base anywhere in the U.S. that can provide comprehensive information about bridge failures, catastrophic or otherwise. The Federal Highway Administration (FHWA) estimates that 50 to 60 bridges fail each year (6), while the U.S. Comptroller General reports that each year an average of 150 U.S. bridges collapse resulting in an average of 12 fatalities (1). For a U.S. bridge population of about 580,000, these two estimates represent an annual failure rate of between 1 in 4,000 and 1 in 10,000.

A study by Harik (2) reviews bridge failures reported in Kentucky as well as nationally. New York State has a database (5) of 823 bridge failures since 1950, 108 of which occurred in the state. Table 1 gives a summary of this database. The Imbsen study (3) reports on bridge failures in 45 states. Failure records are not commonly available, thus individual agencies need to research and review their archives for records and publications in order to determine the failure modes most significant for bridges under their jurisdiction.

TABLE 1. SUMMARY OF BRIDGE FAILURE SURVEY.

| | U.S. BRIDGE FAILURE SURVEY (Since 1950) | NEW YORK BRIDGE FAILURES (Since 1950) |
|---|---|---|
| NUMBER OF IDENTIFIED FAILURES | 823 | 108 |
| NUMBER OF FAILURES DUE TO FAILURE MODE: | | |
| HYDRAULICS | 494 | 43 |
| COLLISION | 108 | 16 |
| OVERLOADS | 84 | 21 |
| NATURE | 24 | 3 |
| MISCELLANEOUS | 39 | 9 |
| FIRE | 24 | 1 |
| DETERIORATION | 36 | 15 |
| EARTHQUAKE | 14 | 0 |

## SIGNIFICANT MODES OF FAILURE

Generally, available data indicates that the majority of bridge failures in the U.S. have occurred on rural, off-system roads and did not generate more than local attention. Harik notes that of 35 bridge failures in Kentucky between 1951 and 1988, only one was widely reported. The Imbsen study and failures in New York State confirm this trend by indicating that over 80 percent of the failures reported in their studies were on local systems.

Because these studies indicate that most bridge failures occur on the local systems, it is important to search for information on such failures through sources knowledgeable about local historical records. Because some states may have unique area characteristics, environmental conditions (e.g., types of loads or geographic peculiarities), or bridge types (e.g., type of construction or material), a study of local historical records is especially beneficial in determining the most significant failure modes for bridges in the area.

Although local bridge failures will indicate most of the significant modes of failure, bridge failures on state and interstate routes may reveal other aspects which cannot be overlooked because of their serious consequences as demonstrated by the Mianus River and Schoharie Creek bridge failures. Thus it would be prudent to identify those failure modes that are significant in terms of their consequences, but are estimated to have a low frequency of occurrence. Earthquake caused failures in the East would be in this category.

As a general rule, the significant bridge failure modes will represent about 90 percent of the area's historical failures. Other failure modes, affecting large geographic areas need to be considered as well. The most significant failure modes can then be prioritized on the basis of their estimated frequency of occurrence and consequences of failure. Although the number of the most significant modes of failure will vary from one area to another, certain modes of failure can be expected to be significant for most areas of the U.S. The State of New York, after extensive study of potential for bridge failures within the state, has identified the six most significant modes of failure for its bridges.

On the basis of available information on bridge failures and closures, the following failure modes appear to be most common:

* Hydraulic: scour/ice/debris
* Overload: design/posted
* Steel Structural Details
* Collision: vehicle/vessel
* Concrete Structrual Details
* Earthquake

Because earthquakes affect a large geographic area and potentially many bridges, they are considered significant. Other failure modes identified but not predominant include failures due to wind, fire, soil conditions, pile deterioration and design/construction errors.

## ASSESSING VULNERABILITY TO FAILURE

Vulnerability of a structure to failure is a measure of its susceptibility to failure or collapse because of loads and/or environmental conditions not anticipated in design. To assess bridge vulnerability, it is necessary to describe it in terms of the structure and site characteristics which contribute to the vulnerability. In general, such characteristics will be specific structural, geometric, design, geographic, geologic or hydraulic features. Assessing the vulnerability of a large bridge population to a number of failure modes is very time consuming, but can be simplified by using a multi-level process.

Such a multi-level process starts with screening the entire bridge population based on specific factors or characteristics relevant to individual failure modes. This is followed by ranking, analyzing, rating, prioritizing and updating. Each level of assessment will successively yield smaller numbers of bridges with higher vulnerability which require a more detailed evaluation. This multi-level assessment process, results in a comprehensive bridge vulnerability rating, and will be discussed in greater detail.

**TABLE 2. CORRELATING CHARACTERISTIC FOR BRIDGE FAILURE POTENTIAL.**

HYDRAULIC

a. Bridges over water

b. Scour history at site

c. Piers or High Abutments
   - Spread footing on soil.
   - Timber piles.
   - Short piles.

OVERLOAD FAILURES

a. Load Posted

b. Non-Redundant

c. Bridge Width <24'

d. Low Operating Rating

STEEL

a. Pin and Hanger Details

b. Welded Details

c. 2 and 3 girder bridges

d. Built before 1978
   (AASHTO Fracture Control Plan)

e. AADTT > 300

COLLISION

a. Bridges over Roadways

b. High Accident History

c. Bridge Geometry
   - Vertical Clearance < 14'
   - Width < 20'

d. Over Navigable Water

e. Barge Traffic

f. Through Structures

CONCRETE

a. Condition Ratings

b. Year Built
   < 1964 (not air entrained)

EARTHQUAKE

a. Built before 1983

b. Multiple Simple Spans

c. High Piers

d. Bearing Type

e. Bridge Seat Support Length

## Screening

The specific characteristics needed to assist in easily identifying structures vulnerable to certain modes of failure can be determined. Typical examples of such characteristics are presented in Table 2. The screening process starts with the total bridge population and uses these characteristics to identify structures vulnerable to a failure mode. For example, only bridges crossing waterways would logically be vulnerable to hydraulic failure, those over navigable water would be vulnerable to water vessel collision, and only those with steel superstructures would be vulnerable to steel superstructure failures. Tables 3 and 4 present typical summary results of a screening process in terms of type of material and bridges over water. Figure 1 is an illustration of six bridges on a screen list for scour vulnerability.

These groups of structures identified by the initial screen can be further subdivided into smaller groups according to a particular failure mechanism that would exist within a failure mode. For example, the steel detail failure mode can be subdivided into pin and hanger, fracture-prone weld details, steel pier caps, eye-bar truss or suspension chain, etc. The result of this screening level of assessment will be a list of bridges vulnerable to a specific failure mode or subset, which will be candidates for the next level of assessment.

TABLE 3. COMPOSITION OF NEW YORK STATE BRIDGES.

| Characteristic | Number of Bridges<br>State<br>(a) | <br>Non-State<br>(b) | (a)+(b) | % of Total |
|---|---|---|---|---|
| Steel | 5,389 | 8,840 | 14,229 | 74 |
| Concrete | 1,722 | 1,468 | 3,190 | 17 |
| Prestressed Concrete | 428 | 606 | 1,034 | 5 |
| Timber | 12 | 277 | 289 | 2 |
| All Other Types | 39 | 392 | 431 | 2 |
| Total | 7,590 | 11,583 | 19,173 | 100 |

TABLE 4. NEW YORK STATE BRIDGES OVER WATER.

| Bridge Characteristic | Number of Bridges<br>State<br>(a) | <br>Non-State<br>(b) | (a)+(b) | % of Total |
|---|---|---|---|---|
| Non-Navigable | 3,539 | 8,015 | 11,554 | 60 |
| Navigable | 132 | 238 | 370 | 2 |
| NYS Canal | 256 | 109 | 365 | 2 |
| Total | 3,927 | 8,362 | 12,289 | 64 |

FIGURE 1. TYPICAL SCREEN CRITERIA AND LIST FOR SCOUR VULNERABILITY.

## SCREENING CRITERIA

TYPE SERVICE CROSSED (TS - 2ND DIGIT)
5 = WATERWAY
6 = HIGHWAY-WATERWAY
7 = RAILROAD-WATERWAY
8 = HIGHWAY-RAILROAD-WATERWAY

PIER PILE TYPE
* = UNKNOWN
1 = NO PILES
8 = TIMBER PILES

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## SCREEN LIST OF BRIDGES OVER WATER WITH TIMBER PILES, NO PILES OR UNKNOWN FOUNDATIONS.

| R | C | BIN | SP# | TS | FEATURE CARRIED | FEATURE CROSSED | [PIER] TY | HGT | F | P | AB PL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 1060240 | 001 | 15 | 73 12011521 | EBR AUSABLE RV | 02 | *** | 6 | 1 | 11 |
| 1 | 3 | 1041250 | 001 | 15 | 214 13021008 | STONY COVER CREEK | 02 | 008 | 0 | 1 | 11 |
| 1 | 4 | 1017000 | 001 | 56 | 22 14071322 | WALLOOMSAC RIVER | 02 | 012 | 6 | 1 | 11 |
| 1 | 4 | 1017000 | 002 | 56 | 22 14071322 | WALLOOMSAC RIVER | 02 | 025 | 7 | 8 | 11 |
| 1 | 4 | 1017000 | 003 | 56 | 22 14407322 | WALLOOMSAC RIVER | 02 | 035 | 7 | 8 | 11 |
| 1 | 4 | 1017000 | 004 | 56 | 22 14407322 | WALLOOMSAC RIVER | 02 | 002 | 1 | 1 | 11 |
| 1 | 5 | 1026350 | 001 | 15 | 50 15021083 | KAYADEROSSERAS CR | 02 | *** | * | * | 11 |
| 1 | 6 | 1054370 | 001 | 15 | 20 16191001 | SCHOHARIE CR | 02 | 033 | 7 | 1 | 11 |
| 1 | 6 | 4038360 | 001 | 15 | 146 16033040 | ERIE CANAL | 02 | 030 | 3 | 1 | 22 |
| 1 | 6 | 4038360 | 002 | 15 | 146 16033040 | ERIE CANAL | 02 | 034 | 3 | 1 | 22 |
| 1 | 6 | 4038360 | 003 | 15 | 146 16033040 | ERIE CANAL | 02 | 032 | 9 | 2 | 22 |

## INVENTORY & INSPECTION DATABASE KEY

R = REGION
C = COUNTY
SP# = SPAN NUMBER
TS = TYPE SERVICE
1ST DIGIT = CARRIED
2ND DIGIT = UNDER

TY = TYPE
HGT = HEIGHT
F = FOOTING TYPE
P = PILE TYPE
AB = ABUTMENT
PL = PILES
1ST DIGIT = BEGIN ABUTMENT
2ND DIGIT = END ABUTMENT

## Ranking

Bridges on the list produced by the screening will not be organized in any order based on their relative extent of vulnerability to the particular failure mode. This can be accomplished by weighting the characteristic indicators according to their relative importance and degree to which they contribute to the vulnerability of an individual bridge. Figure 2 shows an example of the scour vulnerability ranking indicators and their weights. Selecting the indicators and assigning them their relative weights requires experience and good engineering judgement. The Delphi technique (7) can be effectively used for this purpose.

## FIGURE 2. SCOUR VULNERABILITY RANKING.

Scour Vulnerability Ranking = Sum of Waterway, Critical Abutment and Critical Pier Vulnerability Ranking Scores = Range of 0-48 points

| Ranking Factor | Choices | Score |
|---|---|---|
| **A. Waterway -** | | |
| River Slope/Velocity | (steep, medium, mild) | 0-2 points |
| Channel Bottom | (stable, aggrading, degrading) | 0-2 points |
| Channel Configuration | (straight, meandering, braided) | 0-2 points |
| Debris Ice Problem | (yes, no) | 0-1 point |
| Near River Confluence | (yes, no) | 0-1 point |
| Effected by Backwater | (yes, no) | 0-1 point |
| Historic Scour Depth | (none, <1 ft., 1-3 ft., >3 ft.) | 0-3 points |
| Historic Maximum Flood Depth | (<5 ft., 5-10 ft., 10-20 ft., 20-40 ft., >40 ft.) | 0-4 points |
| Adequate Opening | (yes, no) | 0-1 point |
| Overflow/Relief Available | (yes, no) | 0-1 point |
| Simple Spans | (yes, no) | 0-1 point |
| | Range of Score = | 0-19 points |
| **B. Abutment -** | | |
| Scour Countermeasures | (rip rap, wall, cofferdam, not req'd, other, none) | 0-2 points |
| Abutment Foundation | (type of footings and length of piles) | 0-5 points |
| Abutment Location on River Bend | (inside, outside) | 0-1 points |
| Angle of Inclination (Degrees) | (0, 0-20, 20-45, 45-90, >90) | 0-4 points |
| Embankment Encroachment | (small, medium, large) | 0-2 points |
| | Range of Score = | 0-14 points |
| **C. Pier -** | | |
| Scour Countermeasures | (rip rap, wall, cofferdam, other, none) | 0-2 points |
| Pile Foundation | (spread/unknown, piles) | 0-1 points |
| Skew-Angle (Degrees) | (0, 0-20, 20-45, 45-90) | 0-3 points |
| Pier/Pile Bottom Below Streambed | (<4, 4-7, 7-10, 10-15, 15-20, >20) | 0-5 points |
| Pier Width | (<3. 3-5, 5-8, 8-10, >10) | 0-4 points |
| | Range of Score = | 0-15 points |

The result of this ranking level of assessment will be a screen-list organized in order of the extent of the vulnerability to an individual mode of failure. There will be a separate ranked list of bridges for each significant failure mode.

### Analysis

Using the ranked order of bridges in each failure mode, an engineering analysis will be performed. This will specifically address the vulnerability being assessed. The following are some examples of the types of analyses associated with the failure modes:

Hydraulic - hydrologic, hydraulic and scour analysis
Overload - load rating
Collision - impact analysis
Structural Details - remaining fatigue life or load rating
Earthquake - seismic analysis

The analysis is only necessary where the risk or consequence of failure warrants it. Thus, at least initially, an acceptable level of risk within each ranking list must be determined. As the analyses progress down the ranking lists, the results of the successive analyses will define an acceptable level of risk.

The results of these analyses will be used to determine the final vulnerability rating for each bridge in each failure mode.

### Rating

Each list produced by the ranking level of assessment pertains to only one significant mode of failure. All failure modes must be considered, however, in formulating a comprehensive plan for bridge safety assurance. Factors contributing to different failure modes are generally so unique and diverse that no meaningful relationship may exist between them. For example, Pier angle of attack (Hydraulic), frequency of barge traffic (Collision) and bridge seat width (Earthquake). As a result, the ranking values for one failure mode cannot be directly compared with the ranking values for another failure mode. All

TABLE 5. VULNERABILITY RATING SYSTEM

1. **High Priority** - Reasonable expectation of an event which may cause a catastrophic or life-threatening failure. Remedial work desired within 12 months.

2. **Medium Priority** - Possible but unlikely expectation of an event which may cause catastrophic or life-threatening failure. Remedial work desired within three years.

3. **Capital Program Priority** - Reasonable expectation of a failure that could cause traffic disruptions. Remedial work desired to be programmed within five years.

4. **Inspection Action** - Possible but unlikely expectation of a failure that could cause traffic disruptions. Inspection monitoring desired to assure adequate load resistance.

5. **Not Vulnerable** - Adequate structural resistance to this type of vulnerability failure unlikely.

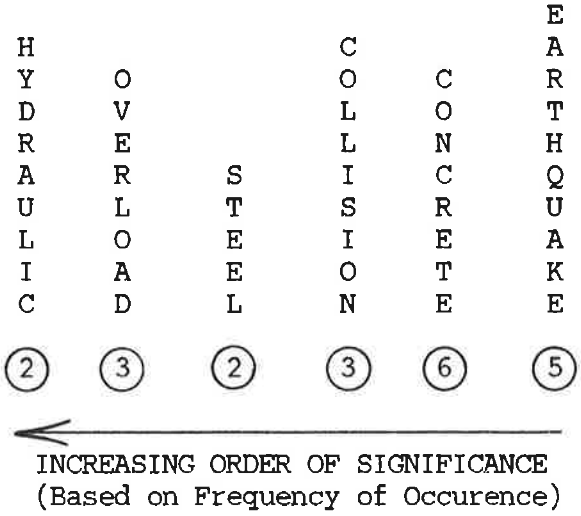
6. **Not Applicable** - No exposure to this type of failure vulnerability.

failure modes have inherently associated with them a certain degree of risk based on frequency of occurrence and consequence of failure causing events. Further, associated with the degree of risk is a consequent requirement for priority of prudent action needed to preclude the possibility of failure. It is possible, thus, to develop a scale/system to rate bridges for vulnerability across different failure modes based on the type and urgency of needed action. Table 5 presents one approach to such a vulnerability rating system. It translates individual failure mode ranking using the related analyses into a common rating scale for purposes of prioritizing actions across the spectrum of all significant modes of failure. The rating scale identifies the urgency for needed action and ties it to the type of action. Figure 3 illustrates a typical six-digit comprehensive vulnerability rating code for a bridge, in a rating system for six significant modes of failure. The result of this rating level of assessment will be ratings of all bridges vulnerable to any of the significant modes of failure.

## Prioritizing

The list produced by the rating level assessment will include all bridges and the degree of vulnerability they have to each mode of failure. There will generally be inadequate resources during a fiscal year, to initiate needed actions for all of the bridges in any one of the rating categories. Thus, it will be necessary to prioritize the bridges based on the rating code. Since there is a desired completion time associated with the first three rating categories, those bridges that have a rating of "1" will take precedent. The list is prioritized by the rating number and then its' position (starting from the left) in the vulnerability rating code. Thus, all bridges with a rating of "1" in the left position (Hydraulic) is given the highest priority followed by the second and so on. The remainder of the bridges, which will have no ratings of "1", will be prioritized by the position of the "2" rating in a similar manner and so on through all six digits of the rating categories. For example, a bridge with the vulnerability rating code of 512365 will have precedence over

FIGURE 3. BRIDGE VULNERABILITY RATING CODE.



RATING CATEGORIES
1 - HIGH PRIORITY
2 - MEDIUM PRIORITY
3 - CAPITAL PROGRAM PRIORITY
4 - INSPECTION ACTION
5 - NOT VULNERABLE
6 - NOT APPLICABLE

a bridge with a rating of 222115. This process will result in a prioritized list of all bridges in order of their extent of vulnerability to any significant mode of failure.

### Updating

The final prioritized rating list of bridges produced in this assessment process must be periodically updated. As the characteristics of the site or bridge can change over time, the vulnerability rating may be affected requiring a new assessment of that bridge, and repositioning it in the prioritized rating list. The frequency of this updating process will depend on local circumstances and resources. Similarly, provision must be made to reassess a bridge after a corrective action has been completed. This updating of the vulnerability assessment will result in a reasonably current prioritized rating list.

## EVALUATION

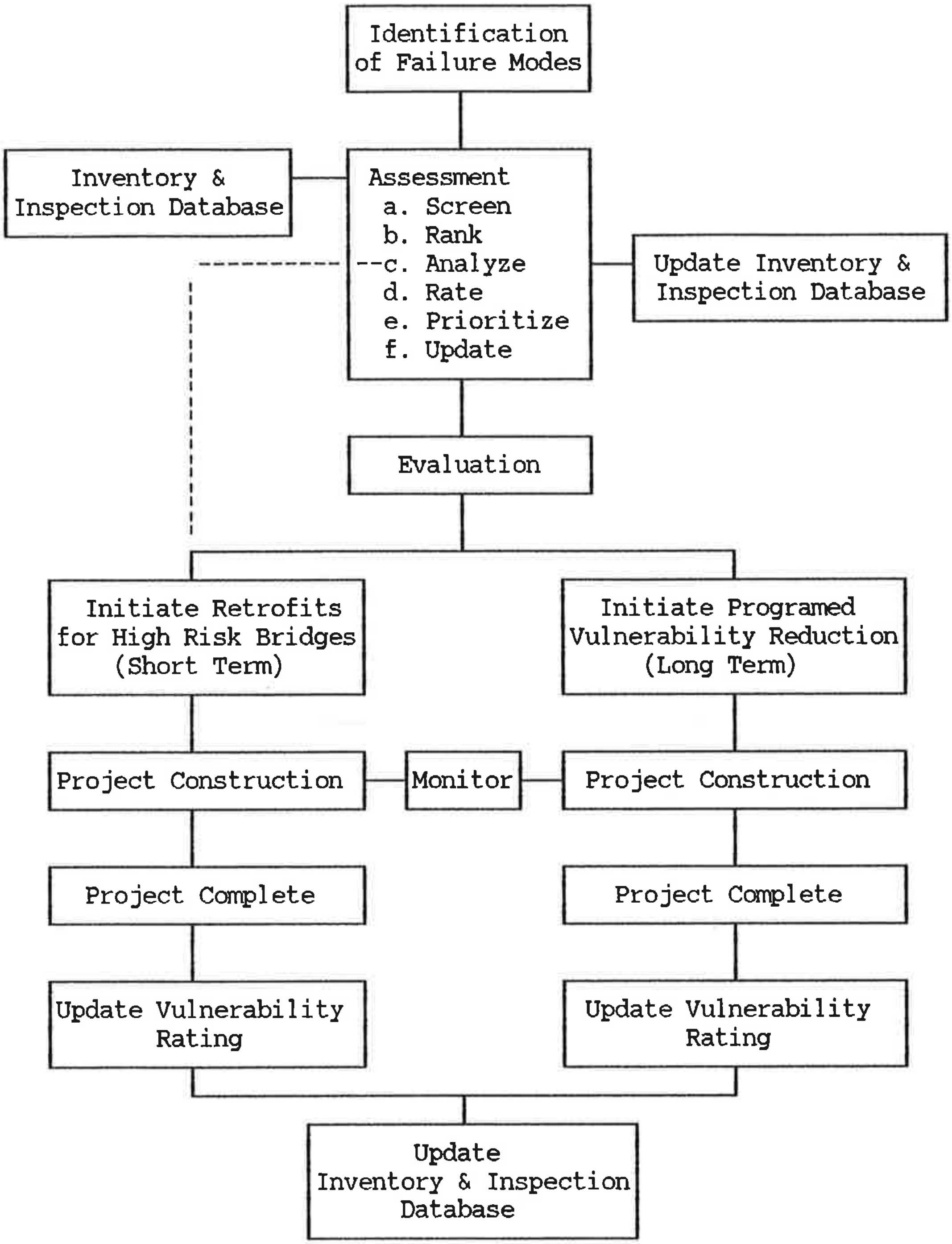
Bridges on the prioritized list will need to be evaluated in the order of their priority. This will consider the overall structural integrity of a bridge subject to all failure modes. The basis of such evaluation will be consideration of current design codes, existing condition, structural capacity, adequacy of structure, vulnerability to all modes of failure, estimate of remaining life, and life cycle costs of rehabilitation alternatives. This level of assessment will result in a structural integrity evaluation report for individual bridges. It will include a discussion of available vulnerability reduction strategies, recommended actions with cost estimates, and a required time schedule for implementation.

## IMPLEMENTATION OF RECOMMENDATIONS

The implementation phase of the program will use the prioritized rating list of bridges as well as structural integrity evaluation reports to program, plan, design and construct projects to eliminate or reduce identified failure vulnerabilities. To achieve both short- and long-term goals, it is essential to identify and program the necessary resources estimated in the evaluation phase. The short term goal should be to implement the priority actions for all bridges with a rating of "1". This will satisfy the need for a prompt response to mitigate the vulnerability of the high risk bridges. The result will be to reclassify the repaired/retrofitted bridges to a reduced or no vulnerability category. Due to the prompt nature of the response, these actions could be of an interim or temporary corrective nature. In such cases, these retrofitted bridges along with those rated with lower urgency of action will be included in the long term goal to further reduce or ideally eliminate the vulnerability. Because long term efforts will be a programmed response, with a permanent corrective action, more time will be needed to design and construct this type of project. This work may be initiated as part of a separate vulnerability reduction program or can be incorporated into the next scheduled rehabilitation or replacement project, depending on the rating and urgency of the corrective action.

As the BSA program is implemented it will be necessary to monitor and report progress. This will provide an overview of the scope and progress of the vulnerability reduction projects. It will also provide information for updating or modifying the program to become more responsive to the dynamic problem of failure vulnerability. The Figure 4 flowchart shows implementation of the BSA program.

FIGURE 4. BRIDGE SAFETY ASSURANCE IMPLEMENTATION FLOWCHART.



## CONCLUSION

Bridges are generally built using state-of-the-art knowledge in design, materials and construction practices. Over time, unanticipated loads and implications of environmental events as well as site condition changes may make a bridge more vulnerable to failure. A comprehensive BSA program will assess this changing vulnerability, and evaluate the structural integrity, and initiate a corrective action on a priority basis to reduce the vulnerability to failure.

The Comprehensive Bridge Safety Assurance Program when fully operational, will permit evaluation of all bridges in a given jurisdiction on a regular basis and provide the current status of the bridge network vulnerability to the significant modes of failure relevant for that area. This program will consist of four phases:

1. Identification of significant failure modes,
2. Assessment of vulnerability of bridges to failure modes,
3. Evaluation of vulnerable bridges, and
4. Implementation of vulnerability reduction recommendations.

Bridge Safety Assurance will become an on-going program with planned periodic updates to account for changing site and bridge conditions. If systematically planned and managed, a comprehensive BSA program will significantly lower the risk of catastrophic bridge failures.

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