NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 426

CAESAR: An Expert System for Evaluation of Scour and Stream Stability

Transportation Research Board
National Research Council

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Report 426

CAESAR: An Expert System for Evaluation of Scour and Stream Stability

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Subject Areas

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation Research Board

This report documents the development and testing of a field-deployable, knowledge-based decision support system that assists bridge inspectors by acquiring, cataloging, storing, and retrieving information necessary for the evaluation of a bridge for the presence of scour. More importantly, the expert system provides an independent scour risk evaluation of the site conditions, evaluates the bridge and substructure elements for failure risk, and provides both explanations of the scour risks and suggestions for scour mitigation. The contents of this report are, therefore, of immediate interest to both highway and rail transit professionals responsible for operating, inspecting, maintaining, and upgrading scour susceptible structures. The report is also of interest to those charged with overall system safety and budgets as well as to policy makers.

The University of Washington in Seattle, Washington, was awarded NCHRP Project 24-06, "Expert System for Stream Stability and Scour Evaluation," to develop an operational, microcomputer-oriented, knowledge-based expert system to advise field personnel in evaluating current and potential scour and stream stability problems and in identifying the urgency for appropriate countermeasures or additional detailed analyses. CAESAR (Catalog And Expert Evaluation of Scour Risk And River Stability), the computer program developed through this project, is available, along with a User's Manual and a growing number of case study files, at the University of Washington's Department of Civil Engineering web site: *http://maximus.ce.washington.edu/~scour/*. It is also available through the TRB Cooperative Research Programs' web site: *http://www2nas.edu/trbcrp/* under All Projects in Research Field E as 24-06 where it is hypertexed as University of Washington. The CRP web site also contains the present status of the project, which is ongoing using FHWA funding to improve program portability and to provide DOT user support. This web site also explains how to borrow an unedited copy of the final report, which contains all of the appendices describing the case studies and the Bayesian network used to model the bridge scour and stream stability domain.

CAESAR offers an organized inspection routine based on entering the answers to specific questions into a laptop computer, ensuring nothing is overlooked. The inspector is aided by extensive help screens amply illustrated with photographs to ensure consistency among inspection personnel. The entered information is combined with static bridge information, such as as-built plan information previously entered in the office, and any previous bridge inspection data before being evaluated using built-in risk evaluation expertise provided by several nationally recognized scour specialists. CAESAR combines these various sources of information and provides specific conclusions concerning the scour risk at piers and abutments. In addition, CAESAR provides general site conclusions for lateral stream stability, vertical stream stability, and contraction scour risk.

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AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 24-6 by the Department of Civil Engineering at the University of Washington. Richard N. Palmer, Professor of Civil Engineering, and George M. Turkiyyah, Associate Professor of Civil Engineering, were the principal investigators. The other author of the report is Paul Harmsen, Graduate Research Assistant. Numerous other individuals contributed both to the background of the report and to the development of the computer model CAESAR (Catalog And Expert Evaluation of Scour Risk And River Stability). Work done at the University of Washington was supervised by Drs. Palmer and Turkiyyah and was performed by the following students: Lea Adams, Suzanne Pollon, Diana Owen, David Landrum, and Paul Harmsen. In addition, numerous experts on scour contributed to the logic in the program and other professionals provided useful editorial reviews of the final report, including Charles Neil, Dave Mueller, Stan Davis, Pete Lagasse, Jimmy D. Lee, Larry Arneson, Martin Fisher, Brooks Booher, Daniel G. Ghere, Jeff Johnson, and Howard Chang. The principal investigators would also like to acknowledge the support and direction provided by the NCHRP project manager, Lloyd Crowther.

CAESAR: AN EXPERT SYSTEM FOR EVALUATION OF SCOUR AND STREAM STABILITY

SUMMARY

This report describes the design, construction, and testing of CAESAR (Catalog And Expert Evaluation of Scour Risk And River Stability), an expert system for the evaluation of scour and stream stability. CAESAR assists bridge scour inspectors with several elements of the bridge scour inspection process, including cross-section plotting; storage of bridge design data; storage of historical scour inspections; note editing and storage; digital photograph storage, viewing, and retrieval; and independent scour risk evaluation. The CAESAR system was field-tested at five state DOT offices across the country. At each state, the system was demonstrated and then used to evaluate typical bridges. The DOT officials compared the system's conclusions with their own conclusions and provided their comments on the system interface. As CAESAR neared completion, it was used to evaluate 25 case studies in order to demonstrate its ability to provide conclusions similar to those provided by human bridge scour experts.

The state DOT officials indicated that CAESAR conforms well with state scour inspection practices and provides adequate features to assist with the bridge scour inspection process. Bridge scour inspectors easily answered the questions posed by the CAESAR system about bridge site characteristics. In addition, the officials indicated that CAESAR could be helpful in organizing inspection records, digital photographs, and other data resulting from bridge inspections. Finally, the officials indicated that CAESAR's conclusions matched their conclusions at the sites visited.

The conclusion of the research is that CAESAR can be readily implemented into state scour inspection processes and will perform its designed function to assist with the bridge scour inspection process and provide an assessment of scour risks at bridge sites.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

There are approximately 500,000 bridges over water in the United States (*1*) and millions of Americans use these bridges daily. Despite their importance, few individuals ponder the integrity of the bridges they use. However, bridges do fail and, when they do, loss of life is almost inevitable. Bridges typically fail for one of two reasons—structural failure or foundation scour. Scour (the removal of sediment from streambeds and streambanks caused by the erosive action of flowing water) is the most common cause of bridge failure in the United States. A 1973 Federal Highway Administration (FHWA) study found that of the 383 bridge failures caused by floods, more than 72 percent were related to scour (*2*).

Recent bridge failures across the country have increased the recognition of the social and economic costs of scour. Indirect costs of bridge failures, such as additional transportation costs associated with a longer alternative route, perished goods, lost wages, and insurance costs, exceeded the cost of bridge repair by more than a factor of five (*1*). Two of the most highly publicized and significant examples of bridge failure are the Hatchie River Bridge failure in Tennessee and the Schoharie Creek Bridge failure in New York. These bridge failures were caused by scour that was not properly identified or corrected (*1*).

In 1988, FHWA issued a technical advisory ([TA] T5140.20), initiating a national scour evaluation program as an integral part of the National Bridge Inspection Program. The technical advisory requires that every bridge over a waterway be evaluated for scour risk and monitored regularly. It is expected that regular scour monitoring will become a common part of either a 2-year bridge inspection cycle or inspections that follow flood events. The initial scour screening inspections of 500,000 bridges were to be completed by January 1, 1997. The technical advisory's requirements constitute a significant undertaking. Steps taken to meet this requirement have highlighted the shortage of qualified personnel to perform evaluations and the lack of consistency in scour evaluations—both among different states and even among inspectors.

RESEARCH OBJECTIVE

The purpose of this NCHRP project was to develop, field-test, and document an expert system to aid in the inspection of bridges with respect to scour and stream stability. The development of this system required the following: acquiring knowledge from noted experts in these topics, encoding this information into an expert system, and testing and evaluating the system in the field. This system provides state highway bridge inspectors with several benefits. The system will improve the quality of the bridge inspections by making available the visual identification capabilities, experience, and knowledge of experts to field inspectors. It also provides site-specific information that might otherwise be unavailable and electronically stores the results of the inspection.

From the outset of this research, there were several clear challenges to reaching the research goals. First, bridge scour and stream stability evaluation is a multidisciplinary endeavor requiring specialized expertise in such diverse fields as fluid mechanics, mathematics, statistics, economics, structural engineering, and sediment transport. The procedures used to evaluate scour, as well as typical mitigative actions, vary among states. Creation of an accurate and reliable decision support system required capturing the diverse knowledge and problem-solving expertise of scour experts and encoding this information into a form usable by field inspectors. The system had to advise bridge inspectors of the appropriate data to observe and the measurements to collect and then how to interpret this information in terms of potential scour risk. These were difficult and challenging tasks.

The time and resources states devote to site observations and scour risk evaluations are limited. Bridge inspectors inspect three or more bridges a day and routinely spend no more than half an hour on inspection items related to the substructure and scour-related factors. Therefore, only easily obtained qualitative and quantitative information is available describing the site, and the decision support system must be able to draw conclusions from this limited information. More sophisticated site characteristics, such as upstream cross-section profiles, 100-year flood discharge, and average bank full-flow velocity, often are not available. Thus, the variables necessary to perform complex engineering calculations, such as pier scour depth and contraction scour, often are not available. The proposed system must provide conclusions using only qualitative variables about the site (e.g., site geometry, visual observations of bank conditions, and historical trends). For the knowledge base to be accurate in the assessment of scour risk at the site, these variables must be formulated in a logic structure that can replace more rigorous engineering calculations.

The final challenge was to generate conclusions that will assist the inspector with the task of screening a bridge for potential scour risk. The domain is complex, inputs are uncertain, evidence may be incomplete, and textual descriptions of the site may inadequately describe site conditions. Despite the lack of detailed site data, the system has to provide accurate and helpful conclusions about the bridge site.

SCOPE OF STUDY

This report describes research leading to the design, construction, and deployment of a knowledge-based expert system for scour inspection that assists with cataloging, storing, and retrieving data associated with bridge inspections and facilitates the evaluation process by analyzing such data to determine the scour risk at the bridge site. The report describes (a) the encoding of knowledge, gathered from numerous experts, into a formal structure representing the bridge scour domain and (b) the use of this structure to assist bridge inspectors with the identification and cause of potential scour risks. In addition, a user interface is described that facilitates cataloging, storing, and retrieval of site-specific information, including photographs of the site and a cross-section profile.

This research has resulted in the development of the CAESAR (Catalog And Expert Evaluation of Scour Risk And River Stability at Bridge Sites) system. This system improves the bridge scour inspection process by providing (1) data cataloging features; (2) the ability to store site observables, notes about the bridge or bridge site, and site photographs; (3) retrieval features that allow for the comparison of historical cross sections and site conditions; and (4) assistance with the bridge scour screening process. The feature providing assistance with the bridge scour screening process is called the decision support feature of CAESAR. The heart of the decision support feature is a Bayesian network. This Bayesian network encodes the knowledge of numerous scour experts and bridge scour literature in a probabilistic representation of the bridge scour domain. Through the decision support feature, CAESAR provides conclusions about the scour processes occurring at the site, severity of scour risks, and suggestions for methods to mitigate these scour risks. The performance of the decision support capability of the system is demonstrated with case studies.

RESEARCH APPROACH

The research necessary to develop the final version of CAESAR was performed in three stages: (1) development of a prototype system, using system logic based on knowledge of one scour expert; (2) refinement of the system, using logic based on knowledge of a panel of scour experts; and (3) field testing and interface development, using case studies and site visits with state DOTs. Initial research focused on the logic needed to encode the bridge scour and stream stability domain and the accompanying initial user interface needed to acquire the necessary variables from the user. The development of the first version of CAESAR's logic, BSES (Bridge Scour Expert System) v1.0, was based on the knowledge and experience of a scour expert, Charles Neill, Principal at Northwest Hydraulic Consultants. Mr. Neill helped develop a list of important variables that should be encoded into the scour domain and the logical relationships between the variables that contribute to a certain scour condition, scour risk, or conclusion. BSES v1.0 was a prototype system useful as a first iteration in developing scour logic, but limited because of both the inputs of a single expert and the limited scope of its logic. Having completed the prototype, a panel of six additional experts was assembled to extend the breadth of expertise surveyed and the sophistication of the logic incorporated in the system.

When critiquing the original model, BSES v1.0, the panel of experts provided three types of suggestions: inclusion of additional variables (observables and intermediate conditions); inclusion of additional or different relationships; and lastly, inclusion of alterations in the relevance between nodes (conditional probability distributions). This second phase of logic acquisition introduced additional factors that were incorporated into the system. Many of these additions included more nodes or variables to describe a particular scour risk (*3*).

These additional variables and relationships were incorporated in the expert system, leading to the next version of the system logic, BSES v2.0. Upon its completion, BSES v2.0 was tested with several case studies obtained from various DOT regional offices. The case studies were used to compare the scour risks identified by the system with those identified by the experts. The system failed to identify several important scour risks, indicating that further refinement in the logic was necessary.

A literature study was launched to determine additional variables and interactions that were important for the representation of the bridge scour and stream stability domain. Most of the information was obtained from several leading scour publications (*1,2,4,5,6*). Several additional scour risks were included in the system logic as a result of this research. In addition, the experts helped establish functional relationships for some variable combinations. Furthermore, the logic was modified to recognize evidence of, and the potential for, lateral migration to the left or right, instead of a general determination of potential for lateral migration. This allowed the logic to assign scour risks to only those piers most influenced by the risk, thus increasing the accuracy and usefulness of the system conclusions. These changes resulted in the third version of the system logic, denoted as CAESAR (Catalog And Expert Evaluation of Scour Risk And River Stability at Bridge Sites).

Initially, CAESAR was tested with nine case studies—the five case studies that were used to evaluate BSES v2.0 and an additional four field evaluations. This version of the logic was found to capture more fully the bridge scour and stream stability domain contained in these case studies. The system identified most of the scour risks identified by the human expert, and the system arrived at the same severity of risk for most identified scour risks. However, these case studies did identify the need for smaller modifications to the logic structure and in the functional relationships between nodes. These modifications were made, creating CAESAR 2.0, and the nine case studies were re-evaluated. This re-evaluation showed that the system could consistently identify and qualify all scour risks represented in these nine case studies. Additional field-testing was performed to test the user interface and system logic by visiting three states (i.e., Illinois, North Carolina, and Arkansas). DOT officials provided comments and suggestions on the user interface and conclusions provided by CAESAR. The logic and user interface were modified in response to these comments leading to the final version of the CAESAR system.

Background on Problem Domain and Solution Method

This research integrates a generic logic framework (Bayesian network) with a specific problem area (bridge scour), using a systems perspective (how will the support software be used?). Accordingly, a review of three topics (the bridge scour inspection process, bridge scour, and Bayesian networks) is provided. The processes and practices of bridge scour inspections are described first. Bridge scour is reviewed by describing what scour is, how it occurs, the components of scour, and the different causes of each component of scour. The section concludes with a description of Bayesian networks and an overview of the strengths of Bayesian networks for application to decision support systems.

INSPECTION PRACTICES

General Bridge Inspection

Bridge inspections identify and quantify the existing conditions at a bridge site and assess potential risks of failure. Bridge inspections have two parts—a structural inspection and a scour inspection. Structural inspections are performed to determine maintenance or repairs necessary to ensure the integrity of the structure. Structural inspectors note conditions such as peeling paint and spaulling concrete. Maintenance actions are suggested if severe conditions exist. Scour inspectors identify scour risks at bridges, assess stream stability, and may suggest the need for countermeasures to protect the bridge from the effects of scour. All state DOT agencies inspect bridges, and all state-owned bridges are inspected for scour risk according to the 1988 FHWA technical advisory ([TA] T5140.20). Structural inspections have been standard practice for most DOT agencies for many years; however, prior to 1988, there was no formal federal mandate for scour inspections. For this reason, state agencies and inspectors are more accustomed to and more familiar with structural evaluations than with scour evaluations. Some states, such as Washington and Oregon, have the same inspectors perform structural evaluations and scour inspections. Other states, such as North Carolina, have different inspectors perform scour evaluations and structural evaluations (*7*). Bridge inspectors work under severe time limitations in the field. Structural evaluations are lengthy, and inspectors typically must perform three or more structural and scour inspections a day (*8*).

Although more time is allocated to structural inspections, scour inspections are arguably more important (most bridge failures are scour-related). However, because of the complexity of the domain and cost of multidisciplinary scour evaluations, thorough hydraulic and scour evaluations are performed only on select bridges. For example, the North Carolina DOT owns 14,000 bridges and 3,000 culverts that must be inspected for scour on a 2-year inspection cycle (*7*). Therefore, bridge scour inspectors perform preliminary scour evaluations to determine if a detailed analysis is needed. The bridge scour and stream stability domain represents a unique problem-solving arena in that these individuals performing this first-level analysis are not domain experts—and in many cases are not engineers.

Bridge Scour Inspection

Scour inspections require both an office review and a field review. Office reviews occur before field inspections. In an office review, the inspector attempts to familiarize himself or herself with the site and bridge, determine the equipment needed for the field evaluation, and identify specific concerns at the bridge site. To become familiar with a site, an inspector reviews previous inspection reports, bridge plans, and aerial photographs of the site (*1*). The data reviewed can be described as static data (i.e., data likely not to change overtime [e.g., number of piers, pier location, deck elevation, and subsurface bed material]) and dynamic data (i.e., data that do change between inspections [e.g., erosion evidence, countermeasure condition, and cross-section profile]).

The field review has four steps: (1) evaluate "screamers," (2) obtain the cross-section profile, (3) observe and record site conditions, and (4) evaluate the scour risk (*7*). Screamers are scour indicators, denoting obvious signs of structural failure due to scour (*4*). Items such as piers or abutments tilting or moving, bridge rail or deck sagging, and blow holes are considered scour screamers.

Cross-section profiles of the stream and overbank are performed by referencing the channel elevation to a known datum such as the rail elevation. This is typically performed by hanging a weighted measuring tape from the bridge rail and measuring the vertical distance from the rail to the bed.

The cross-section profile is important for the identification of scour holes in the cross section and for assessing the magnitude of channel changes, such as shifting thalweg, lateral channel migration, or degraded bed.

The third step in the field evaluation is observing and recording site conditions. The inspection procedure must encourage all scour inspectors to look at site conditions upstream and downstream of the bridge and in the floodplain for evidence of and potential for scour. This information is important for the present scour inspection and serves to help identify changes that occur between inspections. Detailed historical inspection records are extremely important for identifying trends and changes that may threaten the integrity of the bridge.

One of the most important parts of an inspection is the comparison of the current conditions at the site with the conditions during the previous inspection cycle (*8*). The ability to review and compare historical inspections quickly is extremely important for the accuracy and completeness of future inspections. Historical inspection records are particularly useful for detecting and qualifying changes that have occurred at the site that might indicate a potential scour risk (*9*). Engineers performing countermeasure design typically review past inspections of a bridge to determine the type and magnitude of a change occurring at the bridge site, and thereby determine the type of countermeasure most appropriate for the site (*9*). However, past inspections are useful only if they are complete and easily reviewed for changes occurring over time. This is accomplished with a convenient and thorough cataloging and storage method, accompanied by policies directing inspectors to perform thorough scour inspections.

Scour risk evaluation is the most important step in the inspection. All previous steps in the inspection process support the scour risk evaluation. The inspector compares previous cross sections, historical channel elevations, changes in bank conditions, stream location, meander locations, and foundation depths to determine if the bridge is threatened by scour or stream instability. The inspector then assigns a scour code to the bridge. If the inspector suspects a hydraulic problem at the bridge, he or she may note this and suggest that an engineer perform a thorough hydraulic evaluation on the bridge.

In summary, bridge scour inspectors take cross-section profiles, investigate the site, record observations, take photographs (when and where appropriate), and screen bridges for scour risk—reporting those bridges for which they perceive a scour risk to the domain expert. The bridge scour inspection process has been summarized in Table 1.

TABLE 1 Components of a scour inspection

	Task	**Reason for performing task and method used to perform task.**
Office Review	Review previous inspection records, bridge plans, aerial photographs of site	To become familiar with the site, any historical scour problems, and equipment needed for field inspection.
	Determine foundation depth, type, and critical scour depth of pier foundations	To facilitate quick identification of piers with critical embedment during field inspection.
	Confer with maintenance staff and hydraulics personnel	To determine if there are specific concerns that should be noted or closely investigated during field inspection.
Field Inspection	Investigate for screamers	Screamers indicate a severe scour problem at the bridge and suggest the need to close the bridge.
	Obtain cross-section profile	To determine if embedment of any piers is at the critical level, determine if channel has migrated laterally, bed has vertically degraded, or if thalweg has shifted laterally.
	Observe site conditions	Becomes a record of conditions at bridge; site conditions are used to assist with evaluation of scour risk at bridge, countermeasure design, and future bridge design.
	Visually record the site	Typically performed by taking photographs, this visual record of the site is compared with historical records to determine the magnitude of changes that have occurred at the site.
	Evaluate scour risk at site	Determine if local scour is threatening a pier, if the channel or thalweg is migrating, or other scour processes are occurring and then rank the severity of the scour risks to determine actions needed to preserve the bridge.

CAESAR aids bridge scour inspectors by cataloging the important features of a bridge site, storing photographs and cross-section profiles, and providing a quick and convenient method for reviewing past inspections. CAESAR also helps with the assessment of scour risk at the bridge, provides textual explanations of the potential scour risks at the site, increases the accuracy of the bridge scour screening process (i.e., by identifying scour-susceptible bridges), and helps train new inspectors to identify scour problems and causes.

Several computer-based cataloging and retrieval systems already have been implemented in the United States to assist with structural bridge inspections. For example, the Massachusetts Highway Department is using the Integrated Bridge Inspection Information System (IBIIS), which allows collection, storage, retrieval, and distribution of bridge inspection data (*10*). However, a decision support system that allows for the collection, storage, and retrieval of information and that also assists inspectors with scour risk assessment has yet to be implemented in the United States.

CAUSES AND EFFECTS OF SCOUR AND STREAM INSTABILITY

Scour is the removal of sediment (e.g., soils and rocks) from streambeds and streambanks by the erosive action of flowing water. "Although scour may occur at any time, it is usually more significant during high flows, when the water is swift and deep. Swiftly moving water has more energy (turbulence and velocity) to lift and transport sediment than slowly moving water" (*2*).

If the sediment supporting bridge piers and abutments is scoured by a stream, the bridge can become unsafe or fail. Many bridge failures have been caused by scour; some of these have resulted in deaths. In 1987, the Interstate 90 bridge over Schoharie Creek in New York failed because of scour, causing the loss of ten lives. On March 10, 1995, the Interstate 5 bridge over Arroyo Pasajero in California collapsed, and seven people died. After the Schoharie Creek failure, the FHWA mandated that every state must assess bridges for existing scour and identify sites where scour may become a problem (*11*).

Components of Scour

Total scour at highway crossings comprises three components: long-term aggradation and degradation, contraction scour, and local scour (see Figure 1). In addition, lateral migration of the stream must be assessed when evaluating total scour at bridge piers and abutments (*2*).

Aggradation and degradation are long-term streambed elevation changes resulting from natural or human-induced causes that can affect the reach of the river on which the bridge is located. Aggradation involves the deposition of material eroded from the channel banks or watershed upstream of the bridge. Degradation involves the lowering or scouring of the streambed because of a deficiency in the upstream sediment supply (*2*).

Contraction scour is caused by a reduction of the flow area. Contraction scour involves the removal of the bed and bank material across all or most of the bridge opening. This constriction can be caused by the bridge itself, a narrowing of the valley, or other obstructions in the channel that reduce the flow area. The contraction scour results from increased velocities and shear stress on the channel bed (*2*).

Local scour is the removal of material from around piers and abutments. Local scour can be caused by many factors, but the scour mechanism is the same. The mechanism causing local scour at piers or abutments is the formation of vor-

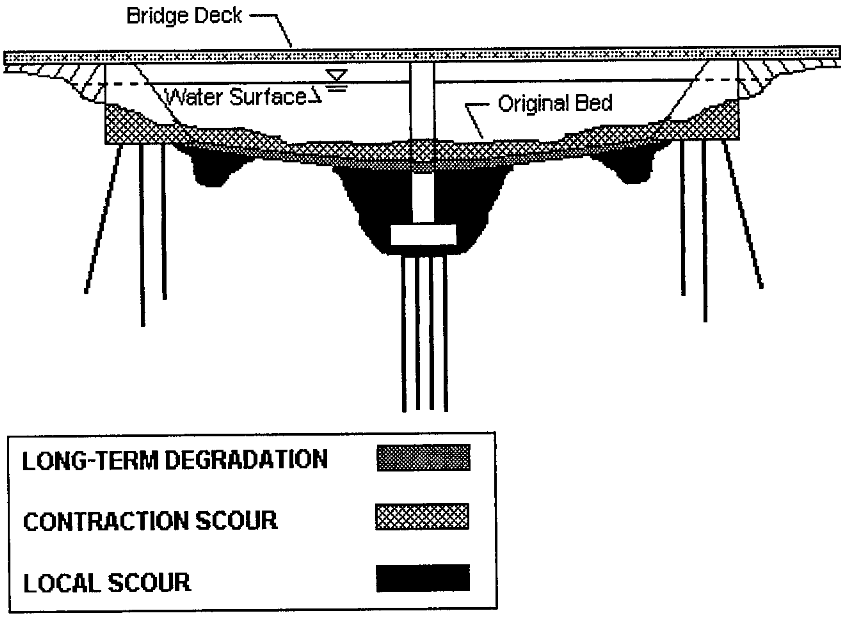


Figure 1. Components of total scour (1).

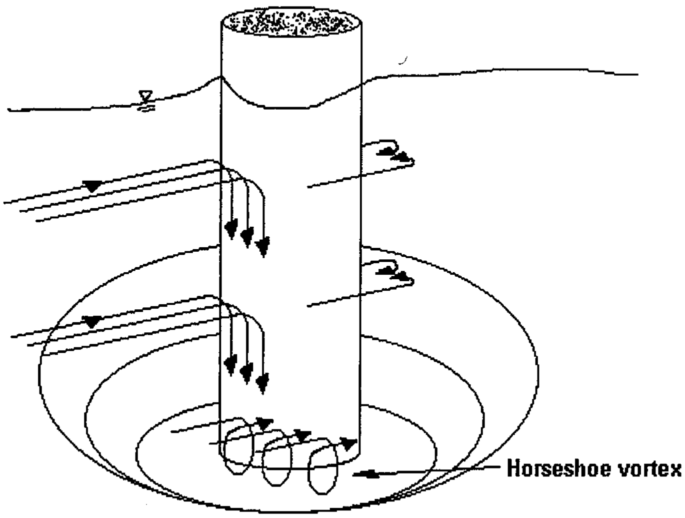


Figure 2. Local scour mechanism at a pier (2).

tices (known as the horseshoe vortex) at their bases (2). The horseshoe vortex removes bed material from around the base of an obstruction to the flow (in this case a pier or abutment). This obstruction to the flow disrupts the sediment equilibrium, that is, the vortex removes sediment from around the base of the obstruction at a greater rate than sediment is supplied to the reach and consequently, a scour hole forms around the base of the obstruction (see Figure 2 for a schematic drawing of a horseshoe vortex at a pier). Factors affecting the magnitude of local scour include, but are not limited to, pier shape, bed material characteristics, debris, angle of attack, flow velocity, flow depth, countermeasures, and flow alignment.

Channel instability can also contribute to scour of the piers and abutments. The factors affecting channel instability include the geomorphology of the stream, the location of the bridge crossing on the stream, flood characteristics, and the material composition of the bed and banks (2). Channel instability is manifested in four primary processes: lateral channel migration, lateral thalweg migration, vertical channel degradation, and vertical thalweg degradation.

BAYESIAN NETWORKS

The most important step in the bridge scour inspection process is the identification and evaluation of scour risks at the bridge site. The determination of risk is accomplished by an analysis of all three components of scour and the identification of the causes of scour and stream instability. Many of these factors are subtle and neither their isolated nor combined effect on bridge stability is fully understood. For this reason, interdisciplinary teams are typically formed when a complete and thorough scour evaluation is needed for a bridge. These teams typically include a geotechnical engineer, a structural engineer, a hydraulic engineer, and a geomorphologist. These individuals attempt to evaluate the combined effects of total scour and stream instability on the stability of the bridge. Teams are needed because the domain is complex; personal experience and knowledge from several disciplines must be compared with existing site conditions in order to evaluate a bridge accurately for scour risk.

The appropriate decision support mechanism and logic representation must be chosen carefully, and it must conform to several criteria. The decision support logic must analyze the site observations, make conclusions about the scour risk, and provide suggested actions to mitigate the risks. To make accurate and reasonable conclusions, this logic must incorporate the knowledge of experts from the fields of hydraulic engineering, geotechnical engineering, geomorphology, and structural engineering.

The successful development of a decision support system for the bridge scour and stream stability domain requires a logic representation scheme that fulfills several requirements: (1) it must be intuitive to domain experts, (2) it must represent the probabilistic relationships among the set of variables involved, (3) it must handle incomplete information, (4) it must provide capabilities for systematic calibration, and (5) it must run in real time on problems involving hundreds of variables. Because a Bayesian network logic representation scheme satisfies all of these requirements, it has been chosen as the logic representation scheme for CAESAR. Appendix A provides an example of a Bayesian network, an explanation of the mathematics associated with Bayesian networks, and a discussion of the justification for use of Bayesian networks for this research. A reader interested in logic selection and implementation is invited to review that appendix in detail.

CHAPTER 2

FINDINGS

This chapter summarizes the features and design of CAESAR, the procedure used to test CAESAR's effectiveness, and testing results. As discussed in the previous chapter, the scour inspection process involves cataloging and retrieving large amounts of information such as site conditions, historical records, and photographs. The primary goal of the inspection process is to evaluate this information systematically and to estimate the scour risk at a bridge site. The determination of scour risk involves a relative weighting of the severity of all types of scour and their causes. The relationships among the different causes of scour and their associated severity are uncertain, and they may differ between sites. These unique properties of the bridge scour inspection process provide CAESAR with the opportunity to help inspectors perform their jobs more efficiently and accurately. Additional information about CAESAR is also available in the User's Manual (*12*), available on-line.

INFORMATION ACQUISITION

A thorough bridge scour inspection requires the acquisition and analysis of two primary types of information related to the bridge and scour. These two types of information are "static" information and "dynamic" information. Static information is information about a bridge that does not change over time. This includes information such as the number of piers, the type of abutments, foundation type, deck elevation, pier locations, as-built channel elevation, and pier shape. Dynamic information may change from inspection to inspection. This includes information such as the cross-section profile, photographs, and visual observations of the site.

Static Information

Static information typically is associated with office reviews. Office reviews include the determination of foundation depth, type, and critical embodiment along with familiarization with the site and any historical scour problems (see Table 1 for a list of inspection tasks). These tasks are accomplished by reviewing aerial photographs, historical inspection reports, and bridge plans. Table 2 lists the types of static information requested. This information is entered into CAESAR in tabular form (Figure 3), and the system produces a schematic of the bridge showing pier positions, foundation type, foundation depths, and as-built channel elevation. The bridge static information is entered once, making it available for review by inspectors for all later inspections. Notes are also stored by the system as static information, thus allowing the inspector to determine if the maintenance or hydraulic staff have identified any specific scour problems at the bridge. Lastly, historical inspection records containing site observables, cross-section profiles, and site photographs are also included as static information that can be reviewed by the inspector to determine historical scour problems or changes that have occurred at the site.

Dynamic Information

The second component of the inspection process is the field inspection, during which dynamic information is recorded. During the field inspection, the inspector determines a cross-section profile, records information about the site, and takes photographs of the site. Table 3 contains a summary of the dynamic information requested by the system, its primary use, and system features facilitating its acquisition.

The first step in the field inspection process is the evaluation of possible scour screamers (site observables that represent clear and present danger to the integrity of the bridge). If no scour screamers are present, the scour inspection process continues by collecting a cross-section profile. CAESAR facilitates the process of recording a cross-section profile and plotting of the profile (Figure 4). The plot contains icons representing foundation and pier types, and the user can plot as many or as few historical cross-section profiles as desired, including the original channel elevation. This feature allows the inspector to detect trends or changes in the cross section that may be threatening the bridge.

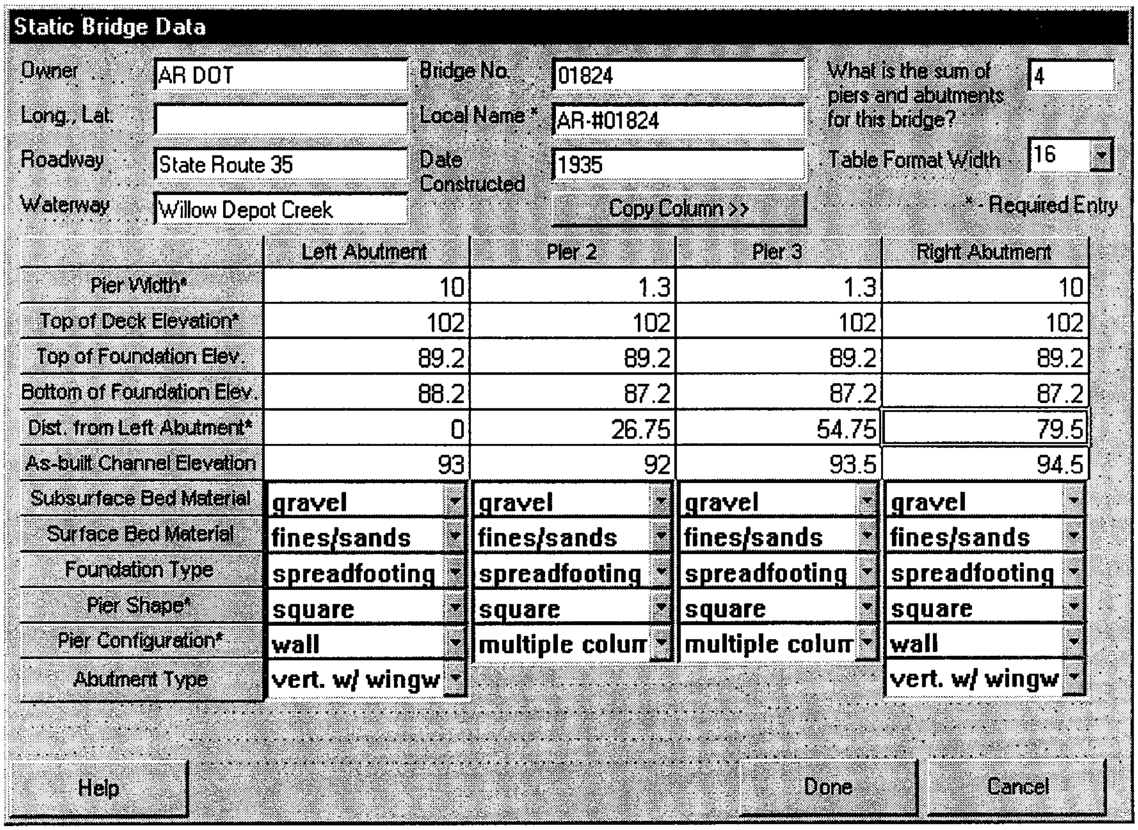
The third component of the field inspection is the retrieval and storage of site-specific information. This is accomplished by responding to questions posed by the system related to stream stability, site geometry, and evidence of scour. This information is used to evaluate the scour risk at the site and as part of the historical record of site conditions. CAESAR facilitates the acquisition of this information by locating all questions in one window called an "inspection

TABLE 2 Static information requested by CAESAR

Static information required by CAESAR	Primary use	System assistance with review or acquisition of information
Pier locations, foundation types, foundation elevations, pier shapes, as-built channel elevations	Inspectors use to determine critical foundation embedment level and to become familiar with the site. System uses information to determine severity of scour risk by analyzing embedment, foundation location, and change of embedment with time.	System help with photographs of foundation types, pier shapes, and pier locations. Data are entered in a concise tabular format, and a cross section is provided showing foundation locations, types, and elevations.
Surface bed material Subsurface bed material	System uses as part of evidence for: foundation stability, contraction scour, and long-term degradation.	System help with photographs of geologic surface and subsurface classifications.
Notes about maintenance work, hydraulic problems, or scour problems	Inspectors use to determine if there are specific concerns noted by the maintenance staff or hydraulics staff.	Note: Editor feature allowing notes to be stored by dates; notes can be added, edited, or deleted.
Historical inspection records	Inspectors use to identify changes at the bridge site by inspecting historical cross-section profiles, photographs, and site observables.	Cross-section plotting feature showing all historical cross-section profiles, site observables (including photographs) stored together for quick review.

form." This form contains 12 different tabs, each containing questions about a specific region of the bridge site or part of the bridge structure. Figure 5 is a screen capture of this inspection form showing all the tabs containing questions about the bridge and bridge site. The 12 tabs are General Site, Bridge, Bridge Site, Cross Section, Downstream, Upstream, Right Abutment, Left Abutment, Bank Stability, Bed Profile Data, Pier Data, and Site Review.

One of the obstacles encountered with the development of a decision support system is the difficulty of expressing the visual characteristics of a site reliably in terms of a prespecified classification and scale. For this reason, extensive on-



Owner: AR DOT
Long., Lat.:
Roadway: State Route 35
Waterway: Willow Depot Creek
Bridge No.: 01824
Local Name *: AR-#01824
Date Constructed: 1935
What is the sum of piers and abutments for this bridge?: 4
Table Format Width: 16
* - Required Entry

	Left Abutment	Pier 2	Pier 3	Right Abutment
Pier Width*	10	1.3	1.3	10
Top of Deck Elevation*	102	102	102	102
Top of Foundation Elev.	89.2	89.2	89.2	89.2
Bottom of Foundation Elev.	88.2	87.2	87.2	87.2
Dist. from Left Abutment*	0	26.75	54.75	79.5
As-built Channel Elevation	93	92	93.5	94.5
Subsurface Bed Material	gravel	gravel	gravel	gravel
Surface Bed Material	fines/sands	fines/sands	fines/sands	fines/sands
Foundation Type	spreadfooting	spreadfooting	spreadfooting	spreadfooting
Pier Shape*	square	square	square	square
Pier Configuration*	wall	multiple colurr	multiple colurr	wall
Abutment Type	vert. w/ wingw			vert. w/ wingw

Figure 3. Table used for entering static bridge information.

TABLE 3 Dynamic information requested by CAESAR

Information requested by bridge scour expert system	Primary use	System assistance with obtaining information
Presence of "scour screamers"	Program warns user that scour screamers" are serious problems and expert should investigate the bridge.	System help and background information about "scour screamers".
Cross-section profile	Inspectors use to determine magnitude of lateral and vertical thalweg stability. System uses to determine severity of total scour, lateral stream migration, thalweg migration, and vertical stream degradation.	Cross-section plotting tool, allowing several reference points to be used as datum. Multiple cross-sections can be plotted simultaneously.
Site photographs	Inspectors use to visually record site conditions and compare with visual observations of previous inspection.	Photograph storage and retrieval feature providing photograph zoom ability.
Erosion severity and location	System uses to assess lateral stream migration and vertical stream instability.	System help with photographs of erosion severity.
Point bar location, size, and vegetation	System uses to assess potential for lateral stream migration.	System help with photographs of point bar type and vegetation.
Instream bar location, size, and vegetation	System uses as part of evidence for: contraction scour and lateral stream instability.	System help with photographs of instream bar type and vegetation.
Abutment specific data: countermeasure presence, serious observables scour, historical scour problems	System uses to assess scour risk and potential for scour at abutments.	System help with photographs of abutment conditions and severity.
Pier specific data: countermeasure presence, serious observables scour, historical scour problems	System uses to assess scour risk and potential for scour at piers.	System help with photographs of abutment conditions and severity.

line help is available for every question posed by the system. Figure 6 illustrates a typical help screen with photographic prompts and textual background information to supplement the question, "What is the extent of floodplain vegetation?"

The scour inspection process is greatly improved by photographs of the bridge site, particularly if they are properly annotated. At future inspections, these notes are reviewed to determine whether long-term trends that threaten the integrity of the bridge or stability of the stream exist. The user can review the photographs of a site through a browsing window (Figure 7). This feature enables the inspector to see changes at a site over time more easily by allowing convenient visual comparisons that probably would not otherwise be available. The inspector can also enlarge each of the images and focus on details in the image with a zoom feature (Figure 8).

INFORMATION EVALUATION FOR DECISION SUPPORT

The most significant and most powerful feature of CAESAR is the logic contained in the decision support system. CAESAR analyzes the site observables, changes in the cross section, and the severity of foundation embedment and then provides an independent scour risk assessment. This assessment assists the inspector by identifying scour risks and evaluating the severity of those risks.

One of CAESAR's outputs includes an evaluation of each substructure element and an evaluation of the overall stream stability. Substructure elemental conclusions are provided in three separate categories: Apparent Ability for Pier/Abutment to Resist Scour, Evidence/Potential of Scour at Pier/Abutment, and Overall Pier/Abutment Stability. Additionally, conclusions are provided for the likelihood of the channel migrating to the left or right, the overall vertical channel stability, and the severity of contraction scour at the bridge. These conclusions are provided as confidence values. For example, one of the overall stream stability conclusions is **Likelihood that Channel is Migrating to the Right**, and the conclusion can have the values of *yes* and *no*. A possible conclusion is: 22 percent yes, 78 percent no; this conclusion indicates that CAESAR is 78 percent confident that the stream is not migrating to the right.

The other component of the system output is a textual paragraph/sentence fragment conclusion that lists specific scour risks, potential threats to substructure elements, and suggestions for mitigation methods. Textual conclusions are

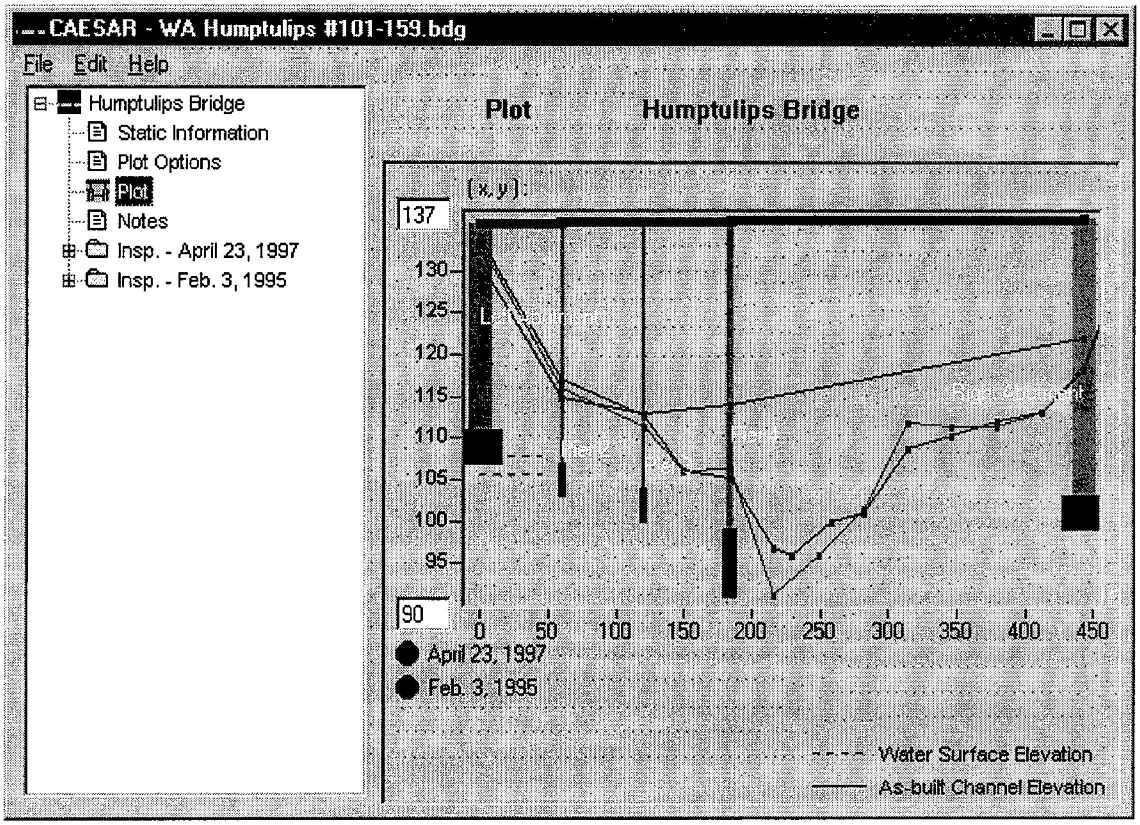
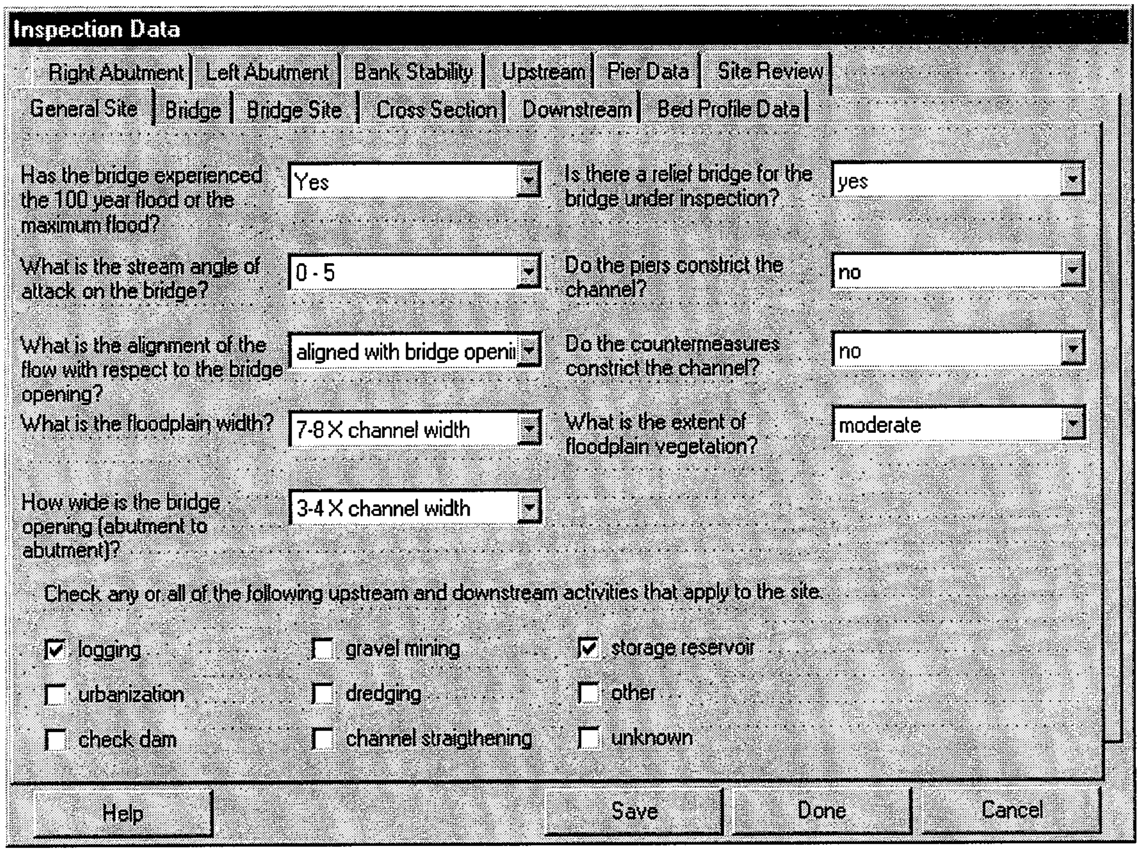


Figure 4. Cross-section profile showing historical changes in cross section.

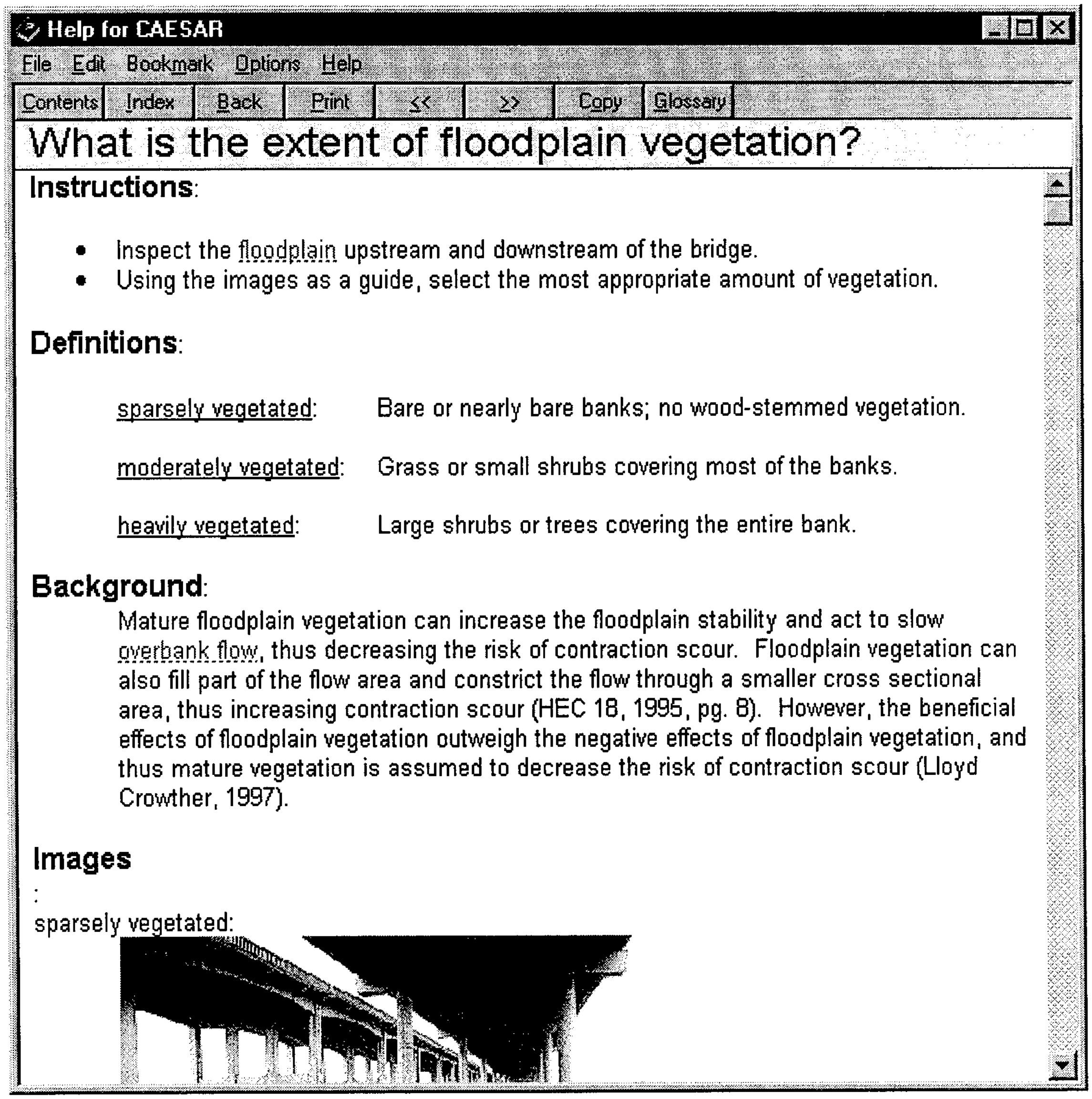


Has the bridge experienced the 100 year flood or the maximum flood?	Yes	Is there a relief bridge for the bridge under inspection?	yes
What is the stream angle of attack on the bridge?	0 - 5	Do the piers constrict the channel?	no
What is the alignment of the flow with respect to the bridge opening?	aligned with bridge openi	Do the countermeasures constrict the channel?	no
What is the floodplain width?	7-8 X channel width	What is the extent of floodplain vegetation?	moderate
How wide is the bridge opening (abutment to abutment)?	3-4 X channel width		

Check any or all of the following upstream and downstream activities that apply to the site:

☑ logging
☐ urbanization
☐ check dam
☐ gravel mining
☐ dredging
☐ channel straigthening
☑ storage reservoir
☐ other
☐ unknown

Figure 5. Inspection form and question tabs.



What is the extent of floodplain vegetation?

Instructions:

- Inspect the floodplain upstream and downstream of the bridge.
- Using the images as a guide, select the most appropriate amount of vegetation.

Definitions:

sparsely vegetated:	Bare or nearly bare banks; no wood-stemmed vegetation.
moderately vegetated:	Grass or small shrubs covering most of the banks.
heavily vegetated:	Large shrubs or trees covering the entire bank.

Background:

Mature floodplain vegetation can increase the floodplain stability and act to slow overbank flow, thus decreasing the risk of contraction scour. Floodplain vegetation can also fill part of the flow area and constrict the flow through a smaller cross sectional area, thus increasing contraction scour (HEC 18, 1995, pg. 8). However, the beneficial effects of floodplain vegetation outweigh the negative effects of floodplain vegetation, and thus mature vegetation is assumed to decrease the risk of contraction scour (Lloyd Crowther, 1997).

Images
:
sparsely vegetated:

Figure 6. Example help window.

made in 33 different subject areas as indicated in Table 4. All scour processes described in Chapter 1, the knowledge and experience of seven national bridge scour experts, and rules taken from current literature on bridge scour have been encoded in a Bayesian network. This logic network analyzes all design information about a bridge and the site information entered during an inspection, and CAESAR then determines an estimated scour risk at the bridge site and identifies the causes of scour risk at the site. The system weighs the information provided by the user, considers all site conditions, arrives at an appropriate conclusion, and states the conclusion in a clear and easily understood format. Table 5 is an example of a textual output automatically generated by the system to aid the inspector in understanding the scour process occurring at a site.

Tracing Logic to Explain Conclusions

The last significant feature of CAESAR is the logic tracing facility. This feature supplements the decision support system by explaining how a particular conclusion is reached. This explanatory process is typically conducted by revealing the chain of logic used to arrive at the conclusion and is typically noted as logic tracing. The logic tracing facility presents (1) the relationship between the various variables entered describing a site and (2) the final node values in the network. By examining the nodes of the network, the site characteristics responsible for the system conclusions can be identified (Figure 9). All subnetworks in the logic can be examined: Pier Logic, Vertical Stream Stability, Lateral Stream Stability, Contraction Scour, and Abutment Logic.

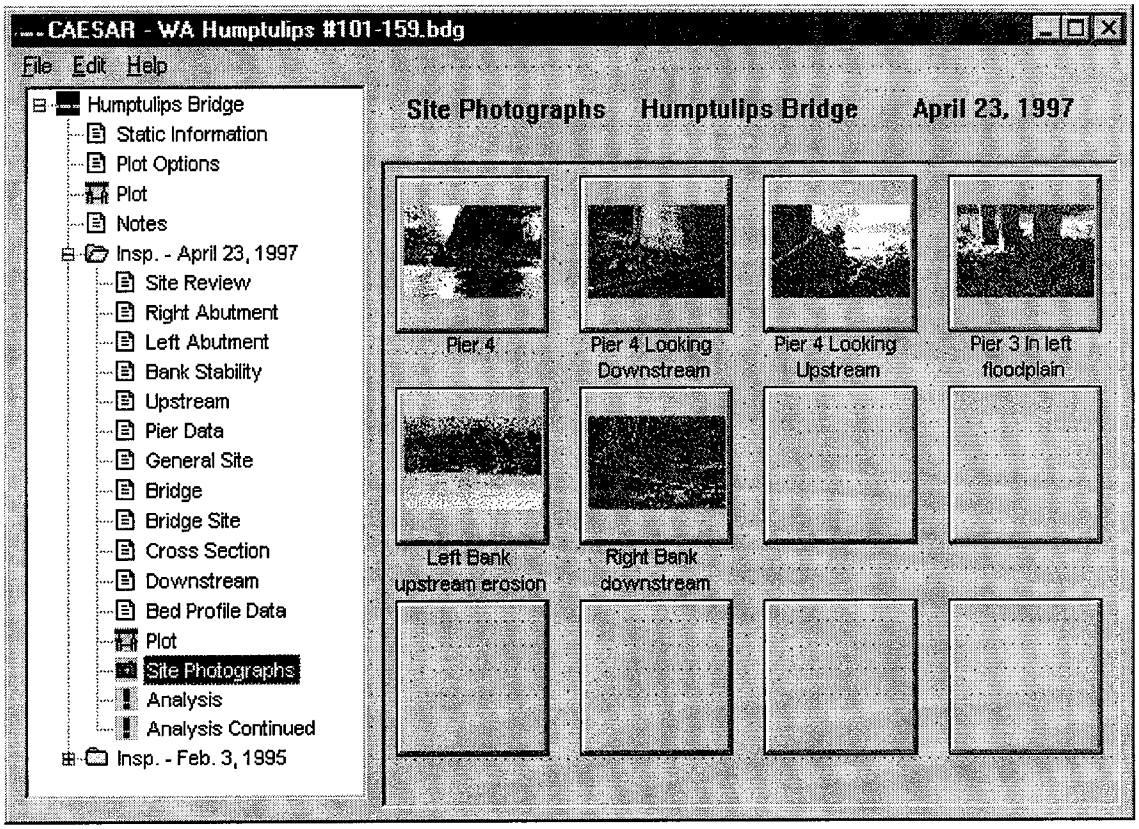
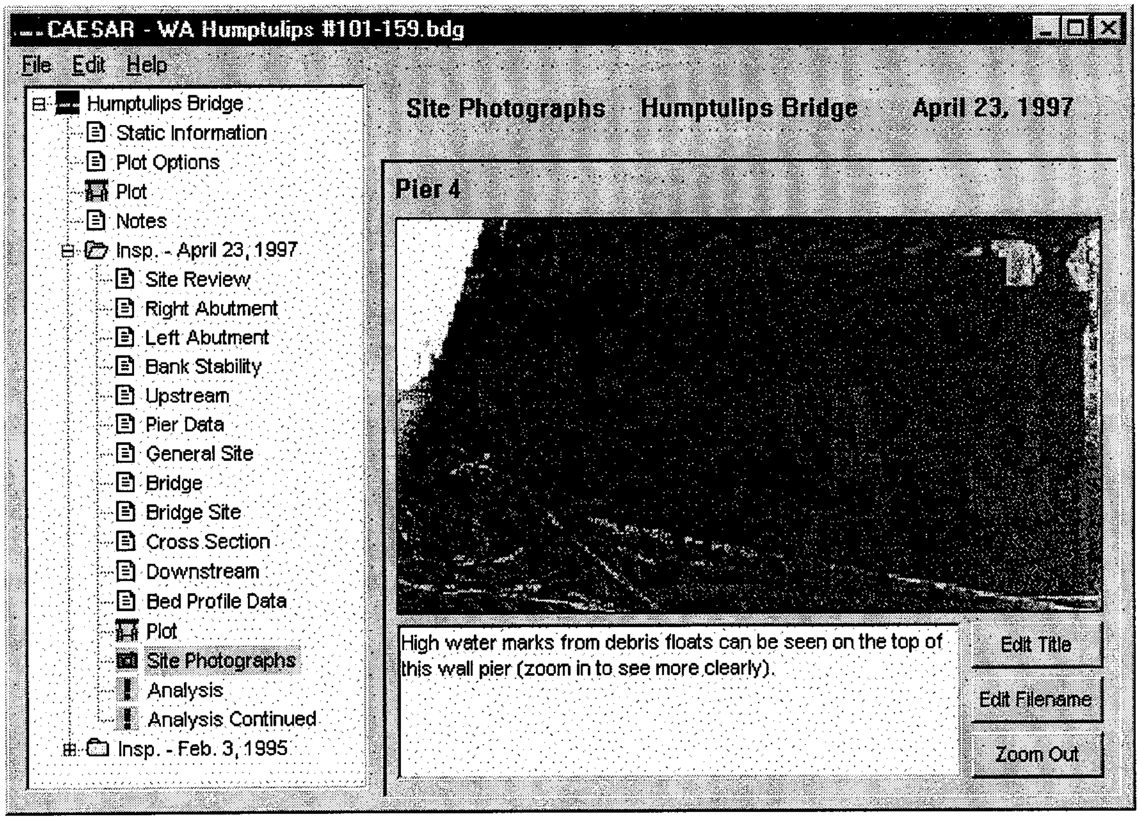


Figure 7. Thumbnail views.



High water marks from debris floats can be seen on the top of this wall pier (zoom in to see more clearly).

Figure 8. Large photograph and zoom feature.

TABLE 4 CAESAR conclusions

1. Expert system Contraction scour is significantly different than calculated contraction scour.
2. Bedrock may erode if it is actually erodible bedrock and the stability of the foundations may be much less than estimated by the system.
3. There is a potential for significant contraction scour at this bridge .
4. Waterway appears inadequate for expected flows.
5. Estimated Total Scour is critical for piers X,Y,Z with known foundations.
6. Total scour for piers X,Y,Z with unknown foundation depths might be critical.
7. Piers X,Y,Z have foundations with unknown type and unknown foundation depths have critical estimated total scour.
8. There is evidence and potential for channel to migrate to the right.
9. There is currently little evidence for the channel to migration to the right, but there is a high potential for lateral migration to the right.
10. There is evidence and potential for channel to migrate to the left.
11. There is currently little evidence for the channel to migration to the left, but there is a high potential for lateral migration to the left.
12. Vertical Thalweg Degradation could cause foundation undermining.
13. Right/Left abutment is threatened by lateral channel migration.
14. Piers X,Y,Z could be undermined by lateral channel migration.
15. Pier countermeasures will probably protect pier from undermining.
16. Pier countermeasures are damaged and thus pier is not protected from undermining.
17. Pier countermeasure installation might decrease scour risk.
18. Vertical Stream Stability could cause scour problems at bridge.
19. Debris in channel should be removed to decrease local scour at piers.
20. Right/Left Bank countermeasures that are present will help control lateral channel migration.
21. Perhaps Right/Left Bank countermeasures should be installed to control lateral channel migration.
22. Right/Left Bank countermeasures should be repaired to help control lateral channel migration.
23. Lateral thalweg migration is threatening piers X,Y,Z.
24. The footings of Piers X,Y,Z are exposed and are resting on scour susceptible material. Perhaps countermeasures should be installed.
25. The pile foundations of Piers X,Y,Z have less than 15 feet of embedment and are embedded in scour susceptible material. Perhaps countermeasures should be installed.
26. The foundation of Piers X,Y,Z are shallowly embedded, but countermeasures may not be necessary, perhaps these foundations should be monitored.
27. The footings of Piers X,Y,Z are shallowly embedded but they are resting on scour resistant material. Perhaps these foundations should be monitored.
28. The footings of Piers X,Y,Z are shallowly embedded but if the countermeasures are maintained then the foundations should be protected from undermining.
29. The piles of Piers X,Y,Z are shallowly embedded but if the countermeasures are maintained then the foundations should be protected from undermining.
30. The piles of Piers X,Y,Z are shallowly embedded, but they are embedded in scour resistant material. Perhaps these foundations should be monitored.
31. The Left/Right abutment is shallowly embedded compared to the potential scour of the abutment. Perhaps countermeasures should be installed.
32. The foundations of Piers X,Y,Z are shallowly embedded, but the bridge appears to have experienced the maximum possible flood, thus the bridge is likely not scour critical.
33. No apparent risks from lateral channel migration, vertical thalweg migration, lateral thalweg migration, or contraction scour.

Node values are displayed when that node is activated. Thus the user can "trace" a particular conclusion to the source variables that contributed most to the conclusion.

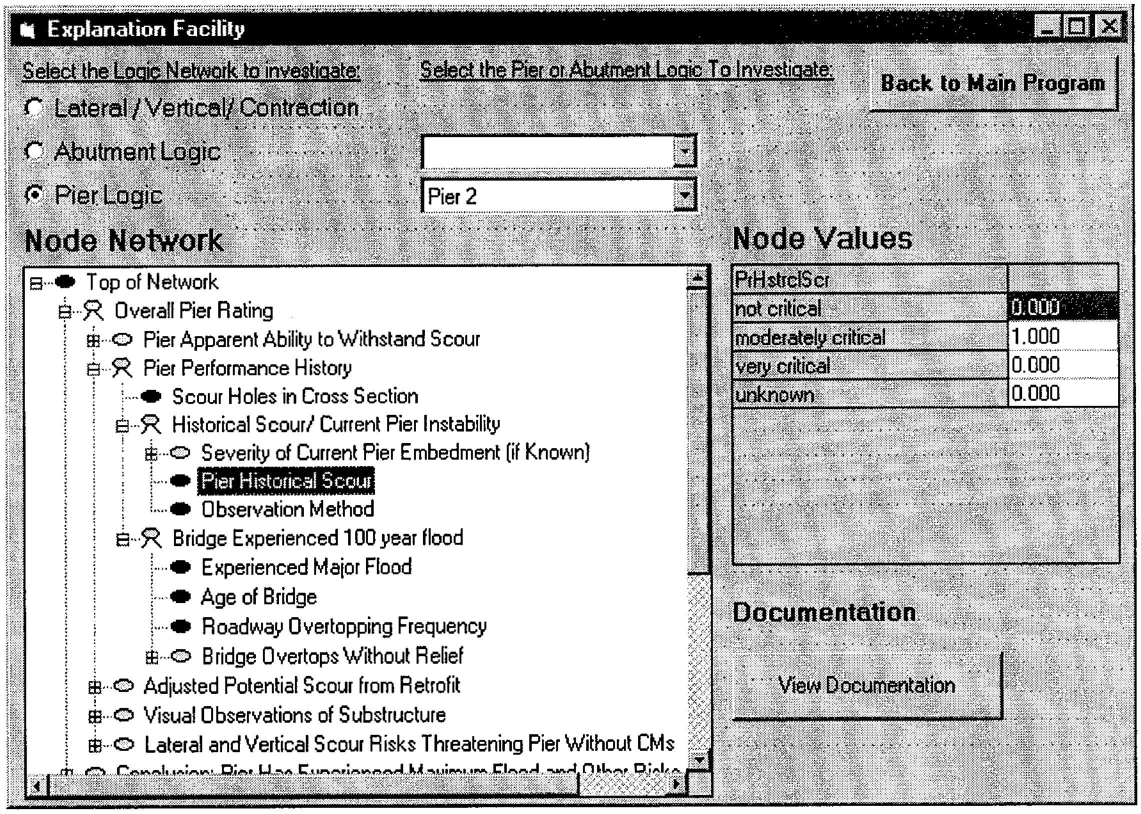
TESTING PROCEDURE

To perform its design purpose, CAESAR must conform to standard inspection practices, it must be useable by inspectors and, most importantly, it must alert the inspector to concerns similar to those that would be raised by experts. The system interface performs all of the cataloging, storing, and retrieving capabilities of CAESAR, and the system logic, encoded as a Bayesian network, performs the decision support capabilities of the system.

The primary measure of a system's decision support capability is the similarity between the system's recommendations and conclusions and the recommendations and conclusions of the experts who have evaluated the same site. The bridge scour and stream stability domain is complex and fraught with uncertainties. For these reasons, the decision support capability of the system was tested at numerous

TABLE 5 Example textual conclusions

Subject	Associated Conclusion
CAESAR's Evaluation Summary	*CAESAR has determined that none of the substructure elements seem to be at severe risk from scour. *CAESAR has determined that the following substructure elements are probably not at risk from scour: Left Abutment, Pier 1, Pier 2, Right Abutment
Pier Foundation Undermining	Pier 4 is at risk of undermining if the channel is allowed to migrate laterally to the left. If the countermeasures at Pier 4 remain undamaged the countermeasures will probably protect this pier from lateral channel migration.
Moving Left	There is evidence and/or potential for the channel to migrate to the left. The following item(s) represent the evidence and potential for the channel to move left (E is evidence, P is Potential) E: Left Bank Erosion upstream, opposite a bend P: Point bar right side of channel at bridge P: Point bar right side of channel upstream of bridge P: Overall left bank stability is low P: Degradation left side of cross section, aggradation right side of cross section
Left Bank cm's	Left bank countermeasure installation at the bridge might help slow lateral channel migration to the left.
Vertical Thalweg Degradation	Pier 4 may be at risk of undermining by vertical thalweg degradation. If the countermeasures at this pier remain undamaged, the cm's should protect the pier from vertical thalweg degradation.



Select the Logic Network to investigate:
○ Lateral / Vertical/ Contraction
○ Abutment Logic
● Pier Logic

Select the Pier or Abutment Logic To Investigate: Pier 2

Node Values

PrHstrclScr	
not critical	0.000
moderately critical	1.000
very critical	0.000
unknown	0.000

Figure 9. Logic tracing feature.

bridge sites. This testing was performed with case studies and/or field visits to several states across the United States, including Washington, Illinois, North Carolina, Arkansas, and Maryland.

Comparisons of expert evaluations and CAESAR evaluations are used to determine the values of five parameters summarizing the accuracy and performance of the system. These parameters are

- Percentage of the risks identified by the experts that were identified by CAESAR,
- Percentage of the risks identified by the experts and CAESAR as being equally severe,
- Number of risks falsely identified by the system,
- Severity of the risks not identified by the system, and
- Percentage of recommendations made by the experts that were also made by CAESAR.

Each expert evaluation consisted of an identification of the scour risks, the causes of the scour risks, and a prediction of the expected bridge failure mode. The system's results and conclusions were compared with the expert's evaluation of the five parameters above.

SYSTEM TESTING

System testing included site visits to four states. State DOT officials were encouraged to use the system before the site visit. The site visits included an overview presentation covering model development, system interface, and case study entry. After questions and comments by the transportation officials, the research team visited several local bridge sites in each state, and CAESAR was used to conduct a scour inspection at each site. This allowed the officials and inspectors to evaluate the system in the field. As part of each site visit, the system's decision support feature was used to analyze the site observations. Through this testing procedure, both the user interface and the decision support portions of the system were evaluated and critiqued.

Interface Testing

The quality of CAESAR's interface relates to its ease of use, amount of time taken to perform an inspection, and its ability to catalog, store, and retrieve observables effectively. Although the DOT officials were not asked to complete a formal critiquing questionnaire, their comments provided the necessary feedback to critique the system interface and to evaluate whether the system could be successfully incorporated into the bridge scour inspection process in that state.

Because the state officials had used the program before the site visit and had observed the use of the program in the field, their comments concerning the interface were used as the basis for determining whether the system would fit into the bridge scour inspection process. These comments are summarized in Table 6.

TABLE 6 DOT officials interface comments

	Interface Comments		
State	**General Comments**	**Recording of Site Observables**	**Features to Assist with inspection**
Illinois	CAESAR can easily be implemented into our bridge scour inspection process with only minor system changes.	Complete and easily retrieval bridge inspection records will greatly help the hydraulic engineers performing retrofit design.	Cross-section plotting tool, photograph cataloging, and store of historical inspections will all provide adequate assistance during an inspection.
North Carolina	System interface has a solid Windows 95® feel and system could be implemented into the scour inspection process with only minor modifications.	Similar site observables are already recorded by scour inspectors, thus system compliments current inspection process.	User should be able to input multiple cross sections, however the feature allowing one cross section might be adequate.
Washington	CAESAR will be used because completing an inspection form will take less than 10 - 15 minutes.	Site observables are already recorded in a similar format, but this electronic storage method would make retrieval of information quicker and easier.	Cross section always taken, thus tool to assist with plotting of cross section is beneficial. Photograph storing and cataloging feature greatly improves record keeping and retrieval.
Arkansas	CAESAR will greatly facilitate inspections, by providing access to the static bridge data, historical cross sections, and ease of data input.	Complete and easily retrieval bridge inspection records will greatly help the hydraulic engineers performing retrofit design.	Cross-section plotting tool and access to historical inspections will allow inspectors to notice significant changes that could threaten the stability of the bridge.

TABLE 7 Summary of case study results

Case Study	Number of risks identified by expert	Number of the same risks identified by CAESAR	Number of actions recommended by expert	Number of actions recommended by system	Actions/ conclusions stated by expert	Actions/ conclusions stated by system
North Toe River, #5, North Carolina	3	3	2	2	Install cm's at abutment, remove debris	Install cm's at abutment, remove debris
French Broad River, #356, North Carolina	2	2	3	2	Monitor Piers 1, Monitor Pier 3, install cm's at Pier 5 and 6	Monitor Piers 3 and 6
South Fork New River, #11, North Carolina	0	0	0	1		Monitor pier 2 and 3
Little River, #180, North Carolina	1	1	0	1		Monitor pier 1 and 2
Buffalo Creek, #184, North Carolina	0	0	0	0		High Overall Rating for all substructure elements
Buffalo Creek, #182, North Carolina	1	0	1	0	Monitor Bent 1 and 2	High Overall Rating for all substructure elements
Elk River, #35, North Carolina	2	2	2	2	Install cm's at abutment, monitor shallow foundations	Install cm's at abutment, monitor shallow foundations
Skykomish River, #2-35, Washington	1	1	2	2	Install cm's at pier and on right bank.	Install cm's at pier and on right bank.
Sultan River, #2-26, Washington	2	2	1	1	Maintain left bank cm's	Maintain left bank cm's
Satsop River, #101-82, Washington	0	0	0	0		High Overall Rating for all substructure elements
Humptulips River, #101-150, Washington	2	2	0	1		Install left bank cm's
Toppenish Creek, #97-116, Washington	3	3	2	2	Install cm's at piers, install cm's at abutments	Install cm's at piers, install cm's at abutments
Quinalt River, #101-160, Washington	0	0	0	0		High Overall Rating for all substructure elements
Yakima River, #24-5, Washington, Prior to cm installation	1	1	2	1	Install flow retardance structures, install cm's at Pier 4	Install cm's at Pier 4
Yakima River, #24-5, Washington, After to cm installation	1	1	1	1	Maintain cm's at Pier 4	Monitor Pier 4
Snohomish River. #522-138, Washington	2	1	2	1	Install bank cm's on right bank, install cm's at Pier 2	Install bank cm's on right bank
Boulder Creek, #101-157, Washington	1	1	1	2	Remove debris	Remove debris, install cm's at shallow piers
Johnson Creek, Maryland, #S009	0	0	0	0	Piles deep enough to withstand scour	High Overall Rating for all substructure elements
Watts Branch River, Maryland, #M-21	0	0	0	0	Piles deep enough to withstand scour	High Overall Rating for all substructure elements
German Branch River, Maryland, #Q32	0	0	0	0	Piles deep enough to withstand scour	High Overall Rating for all substructure elements
Silver Creek, Illinois, # 060-0149	2	2	1	1	Opening undersized, install cm's at each pier	Opening undersized, install cm's at shallowest pier
Sugar Fork Creek, Illinois, #060-0150	2	1	1	1	Install cm's at each pier, potential lateral migration	Potential lateral migration threat
Shoal Creek, Illinois, #003-0024	2	2	0	1		Monitor at shallow piers
Willow Depot Creek #01824, Arkansas	0	0	0	1	Experienced major flood thus stable	Experienced major flood thus stable, install right bank c.m.'s
Rock Creek, #04186, Arkansas	0	0	0	0	Experienced major flood thus stable	Experienced major flood thus stable

As the table indicates, the officials suggested that, with only minor customizations, the system could be implemented in statewide scour inspections and that the program is useful during scour inspections to record site observables and photographs. Furthermore it was indicated that the information storage method of CAESAR (containing notes, bridge cross-section profiles, historical cross sections, and static bridge information) would assist inspectors with the bridge scour risk evaluation step of the scour inspection process. Additionally, the DOT officials stated that CAESAR has a familiar Windows 95® 'look and feel' and that it is the easiest to use and most complete interface (in terms of features facilitating bridge scour inspections) of any bridge scour software available.

The second question, "Can bridge inspectors answer the questions posed by the system?" was answered through scour inspectors performing field evaluations with CAESAR. In each of the visited states, several field inspections were performed. Resident bridge scour inspectors were asked to answer the questions posed by CAESAR as if performing a true scour inspection. The research team also answered the questions posed by CAESAR, allowing a comparison between the researchers' intended answers and the bridge scour inspector's interpretation of the questions and associated answers. Most scour inspectors have experience answering the same types of questions posed by CAESAR, the comparison indicated that, indeed, the inspectors could answer the questions accurately. Furthermore the inspectors stated that the question layout and formatting was easy to follow and learn. The inspectors also indicated that the on-line Help function was beneficial for determining the purpose and meaning of the questions posed by the expert system.

System Logic Testing

The most significant and important feature of CAESAR is its ability to assist with the identification and qualification of scour risk at a bridge site. This feature, however, is only beneficial if the system consistently supplies the kinds of conclusions that experts provide at various bridge sites experiencing a range of scour risks. To test the decision support feature of the system, 25 case studies were evaluated. A case study consists of the static information about a bridge, historical cross sections, past inspection records, and an evaluation of the scour risk at the site. Furthermore, 18 of the sites tested on the system were visited in the field to obtain current site observables. For the remaining seven bridges, site-observable information was obtained from the site descriptions provided in the case study reports.

TABLE 8 CAESAR case study performance

What percentage of the risks identified by the expert were also identified by CAESAR?	89%
What percentage of the risks identified by the expert did the system state to be of equal severity?	82%
What was the severity of the risks not identified by the system?	Minor
How many risks did the system falsely identify?	2
What percentage of scour risk mitigation recommendations made by the expert were also made at least as conservatively by the system?	75%

CAESAR was used to conduct the scour inspections at each of the bridges visited to determine the scour risk at the site. The results, conclusions, and recommendations provided by the system were then compared with the experts' evaluation of the site. Thus, by comparing the experts' evaluation and the system's evaluation, the five performance questions could be answered.

Case Study Summaries

The results from the 25 case studies are summarized in Table 7. This table lists, for each case study the number of risks identified, number of actions recommended, and the specific conclusions provided by both the experts and CAESAR. Appendix B contains a more thorough description of each case study, including a brief description of the site, the experts' evaluation of the site, CAESAR's evaluation of the site, and a critique of the system's evaluation with respect to the five performance parameters. The summaries in Appendix B are extremely important because all the scour risks and the recommendations are listed individually, and the comparison of these lists is the basis for the critique of CAESAR's decision support facility.

Table 8 presents a more concise summary of the case study results. This table suggests that CAESAR was successful in identifying and evaluating numerous risks identified by the experts who evaluated these 25 case studies. These case studies presented settings where a wide variety of scour processes were threatening bridges. These processes included lateral channel migration, lateral thalweg migration, vertical thalweg degradation, contraction scour, and local scour. The system was able to identify all of these risks when the risks were present. Furthermore, the system typically correctly identified the specific substructure elements that were threatened. Chapter 3 provides an interpretation of these results.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

INTERPRETATION

The goal of testing CAESAR with 25 case studies was to determine if the system could identify a wide range of scour concerns on streams and rivers with different hydrologic and geomorphological characteristics. This process is not simple and is considerably more subtle than direct analysis of a laboratory experiment. Testing the performance of CAESAR required interpretation of scour evaluations performed by state DOT personnel and consultants, and comparisons with the output of CAESAR. Scour evaluation is complex and requires careful evaluation and consideration of numerous types of inputs. Interpretation of historical and field data and their relevance to a specific situation is required.

While the researchers have attempted to summarize herein the DOT personnel evaluations and CAESAR's output, the reader is encouraged to explore Appendix C to fully appreciate the degree to which CAESAR was able to mimic the performance of the individuals who performed the scour evaluations.

Table 8 indicated that CAESAR was successful in the identification and qualification of numerous risks identified by the experts who evaluated these 25 case studies. Thus, these case studies provide evidence that CAESAR's decision support feature can provide accurate conclusions to supplement a bridge inspector's independent site evaluation. However, as indicated in Table 8, CAESAR does not provide the same conclusions as the experts for all bridge sites; an inspection of the instances when CAESAR's conclusions differ from the experts provides a greater understanding of the accuracy of CAESAR's decision support system.

Despite several differences between CAESAR's conclusions and the experts' conclusions, the system can make accurate and meaningful recommendations for most of the bridge sites tested. The system identified 89 percent of the risks identified by the experts and typically suggested countermeasures at the same substructure elements or at the same banks suggested by the experts.

Although for most of the case studies the system identifies the same risks and concludes the risks to be equally severe as the experts, in two of the case studies the system labeled the scour risks as less severe than stated by the experts. In both of these case studies, the experts suggested countermeasures at all piers. The system identified local scour as only a minor risk on both of these bridges and did not recommend monitoring or countermeasures. However, CAESAR's results can still be considered accurate for several reasons. First, the recommendation to install countermeasures was based purely on the calculated total scour (sum of local and contraction scour), but the local scour and contraction scour calculations are consistently overly conservative (*9*). Second, the pile foundations of the first bridge are embedded 32 ft, and the foundations of the second bridge are embedded 55 ft.

In addition, the system falsely identified several risks. For the Boulder Creek case study, CAESAR recommended countermeasures at three piers that were shallowly embedded in cobbles (about 5 ft of embedment). Typically, this would be considered a critical level of embedment, but the creek is a low-volume, mountainous stream with little scour potential, and CAESAR failed to weigh these factors more than the limited foundation embedment—the result being conservative scour risk conclusions. In the Shoal Creek case study, the system identified multiple piers that could be threatened by scour, but the expert did not identify these piers to be at risk. The system recommended monitoring of the shallow Shoal Creek piers, and thus the system was slightly conservative in its conclusions for this case study.

The system failed to identify only two risks in the 25 case studies: (1) risk of migrating confluence of the Skykomish and Snoqualmie Rivers in the Snohomish River Bridge case study and (2) risk of total scour at the North Carolina, Buffalo Creek Bridge, #182 case study. The migrating confluence in the Snohomish River is causing erosion and other signs of scour, which the system identified as lateral channel migration. Given that the system labeled the migrating confluence as an equally severe scour risk (lateral channel migration), the system is still effective in identifying the bridge as "at risk" from scour. The experts recommended post-flood monitoring of the foundations on the Buffalo Creek Bridge, but the system did not label the risk as severe enough to recommend monitoring. Thus, in this one case study, the system was slightly nonconservative.

Lastly, the system is capable of suggesting accurate and meaningful recommendations as well. Typically when an expert suggested countermeasures at a pier or abutment, or bank countermeasures, then the system suggested countermeasures at the same substructure elements or at the same banks. Furthermore, the system recognized the importance of subsurface material, and in several instances the system suggested that the user verify the entered subsurface bed materials in order to verify the system resuts.

APPRAISAL AND APPLICATIONS

System testing, comments from DOT officials, and interpretation of testing results indicate that CAESAR can be implemented in the scour inspection procedure of all state DOT offices across the country. CAESAR can significantly affect how bridge inspections are performed and used for decision making. Inspectors can have automated access to all pertinent design information about a bridge, including all historical inspection records, maintenance records, cross-section profiles, photographs, and scour risk history. This system will improve the efficiency of the bridge scour inspection process, the accuracy of inspections, and the consistency between inspections. Most important, the system can help the inspector to identify and qualify scour risks at the bridge site; early detection and identification of scour risks will decrease the number of bridges lost to scour.

The CAESAR system for assistance with bridge scour inspections is available at the University of Washington's Department of Civil Engineering web site: http://maximus.ce.washington.edu/~scour/. Also available on the web site are the case study files used to test the system and a User's Manual.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

SUMMARY

This report describes the bridge scour inspection processes, problems associated with current inspection practices, and the development of a system designed to assist with cataloging, retrieving, and storing bridge site observables and the evaluation of the observables for possible scour risk. The report begins with a review of scour processes and scour evaluation processes, leading to the initial decision support logic and user interface (*3*). The system has matured with several iterations of logic improvement, including reviews by bridge scour experts, case study tests, and field tests. These improvements have lead to the development of CAESAR, a system providing assistance with the collection, cataloging, and retrieval of site observations, including cross-section profiles, site photographs, and numerous other variables. The expert system analyzes site observations through the use of a Bayesian network and provides conclusions similar to those of human experts pertaining to the apparent scour risks at the site and suggestions for possible scour mitigation actions.

Both the user interface and the decision support feature of CAESAR were tested. The interface was evaluated by the individuals responsible for orchestrating bridge preservation through inspection, maintenance, and countermeasure installation. The decision support feature of CAESAR was critiqued through 25 case studies. These case studies represented a wide variety of scour risks and site conditions. Each case study contained the experts' evaluation of the site and recommended scour mitigation actions for comparison with CAESAR's evaluation and suggestions. The case study testing procedure indicated that CAESAR could identify 89 percent of the scour risks identified by the experts, and CAESAR estimated the severity of 82 percent of the scour risks *to be equal to the severity* identified by the experts. Furthermore, *the experts' scour risk mitigation recommendations were made at least as conservatively by CAESAR 75 percent of time.*

CONCLUSIONS

The research, development, critique, and testing that has led to the development of CAESAR has highlighted several important conclusions:

1. The selected logic representation scheme, a Bayesian network, proved capable of modeling the bridge scour and stream stability domain. The Bayesian network can be used to generate conclusions and recommendations easily, to provide sensitivity analysis, and to include the cost of observing variables in the analysis.
2. CAESAR consistently identified the scour risks in all 25 case studies evaluated. The case studies represented bridges experiencing a wide variety of scour risks. In most cases, CAESAR produced results identical to those of the scour experts.
3. State DOT officials indicated that CAESAR's interface provides adequate features for cataloging and storing bridge scour inspections, that the system provides reasonable conclusions, and that the system could be implemented into the state scour inspection procedure.
4. Bridge scour and stream stability is a complex domain. Many variables are needed to analyze difficult situations. However, many of these variables do not influence all conclusions and can be omitted during certain inspections; therefore, CAESAR must be capable of indicating to the user those variables exerting significant influence on specific conclusions for which accuracy is critical.
5. State DOTs should be encouraged to integrate CAESAR into their inspection processes to provide more consistent, organized, and complete bridge scour evaluations.

FUTURE RESEARCH AND SYSTEM ENHANCEMENTS

1. Continued evaluation of CAESAR using case studies will help to generate confidence in its results and provide valuable insights into situations where its logic cannot identify subtle causes of scour and stream instability.
2. State DOTs should explore the opportunity to customize the system for their unique geologic, geographic, and stream geomorphologies by developing state-specific logic weighting within the model.
3. The value of organizing multiple bridge files by stream, highway, or the county in which the bridge is located should be explored. This organization would facilitate retrieval of information and would allow inspectors to combine the bridges for which they are responsible into

one file. A related enhancement would be the capability to display on a map all the bridge names, locations, and rivers/streams on file for a county. This would further facilitate data retrieval and increase the ease of use of the program.

4. An important enhancement to CAESAR is the inclusion of incremental acquisition and post-evaluation sensitivity analysis features. Incremental acquisition of variables would allow for efficient data input; the user would need to enter only the information necessary for an accurate site evaluation. Post-evaluation sensitivity analysis would be performed for each conclusion and would indicate to the user those variables most influential for each conclusion.
5. Several additional enhancements should be developed that rely on the cross-section profile to provide more conclusions and recommendations. These enhancements include automated identification of bed degradation, lateral thalweg shift, vertical thalweg degradation, and lateral migration of channel. This analysis would enable CAESAR to provide detailed warning messages to the inspectors. A related enhancement would be the ability to input multiple cross sections for one bridge. These multiple cross sections would enable the system to make both longitudinal and lateral comparisons of cross sections and detect trends in the cross sections that indicate scour risks at the site.
6. The integration of CAESAR with a fully implemented geographic information system (GIS) system could enable CAESAR to provide more thorough, accurate, and intuitive conclusions and recommendations. Regional variables, such as flood events, floodplain deforestation, or channel dredging, could be associated with multiple bridge sites. This would simplify data entry, enable regional association of variables, and allow CAESAR to provide conclusions about problems that could arise at downstream or upstream bridges because of regional changes.
7. When a scour expert investigates a bridge site, the spatial orientation of the site has a significant influence on the determination of scour risk. Information such as stream depth, distance to upstream bends, location of bars, and location of confluences all influence the conclusion. CAESAR could better mimic scour experts' conclusions if this spatial orientation information were entered into the system. A graphically based data input method would be the best means for incorporating this information into CAESAR's decision support logic.

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APPENDIXES A THROUGH E

UNPUBLISHED MATERIAL

Appendixes A through E as submitted by the research agency are not published herein. For a limited time, they are available for loan on request to the NCHRP. Their titles are as follows:

Appendix A:	Bayesian Networks
Appendix B:	Decision Support Testing and Results
Appendix C:	Overview of System Logic
Appendix D:	Complete Logic Documentation
Appendix E:	Bibliography

The **Transportation Research Board** is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation