GIS-Based Bridge Scour Prioritization

By

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ABSTRACT

A bridge scour prioritization scheme is developed using the advantages of a geographical Information System (GIS) analysis. The scheme was developed to assist in the allocation of resources for bridge remediation and repair. A GIS is created for each New England state to geographically integrate bridge, dam, and gage infrastructure in order to recognize the relation between them. Bridge data are based on known characteristics of the bridges. Because many of the bridges have unknown designs, the Connecticut Comparative Scour Analysis is incorporated in the evaluation of the bridge scour susceptibility. Preliminary analyses have been conducted and compiled into two tables, a gage table and a scour table. The gage table contains data pertinent to recurrence levels at stream gage sites. The scour table contains data pertinent to the flood levels to result in significant scour hazard. The combination of the two data sets results in an analysis that assigns return periods for scour susceptibility. The return periods can be used as a measure of prioritization. The GIS allows for spatially relevant evaluation of the gage data and scour data as well as the presentation of the results in map form.

INTRODUCTION

Bridge scour, or the erosion of the sediments from the streambeds and stream banks, is recognized as the most common cause of bridge failures. According to Shirhole and Holt, sixty percent of all bridge failures since 1950 could be attributed to the effects of flow hydraulics. Annual federal aid for scour related bridge failures and repairs for flood damage to bridges are approximately $30 million to $50 million. The flow regime is made even more complex because of the bridge piers and abutments. When one considers that 84% of the nations 575,000 bridges span a waterway (National Bridge Inventory) the need for a comprehensive and rational means for categorizing the bridges was necessary. To fully characterize the factors that influence bridge scour it is necessary to understand channel and bridge geometry, floodplain characteristics, flow hydraulics, bed material, channel protection, channel stability, riprap placement, ice formations and debris (Richardson and Davis, 1995).

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Although bridge scour has long been observed, the problem first received nationl attention whe the I-90 bridge over Schoharie Creek, New York, failed on 5 April 1987 causing two spans of the bridge to fall into the floodwaters, subsequently resulting in ten deaths. The investigations by the National Transportation Safety Board determined that the cause of the failure was based on inadequate riprap around the piers and a shallow foundation depth, items that could have been addressed if these problems were identified prior to the flood. This resulted in an effort by the Federal Highway Administration (FHWA) to mandate the identification of bridges at risk of scour susctiblity through quantitative and qualitative means.

The FHWA issued technical advisories in 1988 and 1991 (USDOT, 1988, 1991) to provide states with the means for implementing a scour evaluation program for existing bridges and new bridge designs. FHWA issued two Hydraulic Engineering Circulars, HEC-18 and HEC-20) with design, evaluation and inspection procedures for bridge scour (Richardson and Davis 1995). In using the prescribed method of analysis is the development of a single digit rating system of the National Bridge Inspection Standards (NBIS) (USDOT 1995).

Although a logical means for evaluating bridge scour was created, the implementation has not been easy to execute. Bridge scour evaluation requires a multidisciplinary approach. On top of this, the effort requires significant archival research in the design of existing bridges, flow conditions, and hydrological predictive models. Data on as built conditions of bridges is not easily gleaned. Foundations of many older bridges are completely unknown. It isn't always clear how multiple or parallel spans are to be treated when cataloging the bridges. A geographical information system (GIS) is an effective means for spatially storing the database, analyzing the data and presenting results of the analysis.

NBIS rating

Through the NBIS, scour critical bridges are addressed in the Item 113 code in the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (Report No. FHWA-PD-96-001). A bridge is classified as scour critical according to one of the following: (1) observed scour at the bridge site or (2) scour potential as determined by a scour evaluation study. A single digit code is used to describe the stability of the bridge and its vulnerability to scour. Descriptions for all Item 113 codes are presented in Appendix A. Scour critical bridges are identified by a code of 0, 1, 2, or 3, with 0 indicating that the bridge has failed (U.S. Department of Transportation 1995).

Over the past ten years, state DOTs in New England have devoted a large amount of time to assigning Item 113 codes for each bridge. While states have coded the majority of their bridges, no state has completely finished the task as many bridges either still need to be evaluated or were assigned a temporary code until more thorough analyses could be performed. Codes were assigned to many structures after an initial screening was conducted, without the need for a full scour analysis. For other bridges, the initial screening was not sufficient, requiring instead a more comprehensive scour analysis to assign a code. Many of the older structures could not be thoroughly evaluated since no plans were available and the foundations were thus unknown. In other cases, hydraulic or

Federal Emergency Management Agency (FEMA) studies were not available or complex hydraulic conditions at a bridge site necessitated an even more intensive analysis.

There are two approaches for assigning Item 113 codes to bridges with unknown foundations. One is to code the bridge as a 3 (scour critical). This is done to save time and money and is based upon results of other similar bridges that have received full scour evaluations. Another approach is to code the bridge as U (unknown foundation) until subsurface investigations can be performed based upon prioritization. The investigations can be accomplished through borings or geophysical testing methods such as ground penetrating radar. While this approach is more costly, it permits a full scour evaluation to be conducted, potentially removing some bridges from the scour critical list.

HEC-18 Evaluation

DOTs evaluate their bridge inventory for scour susceptibility using a number of different scour methodologies, the most common of which is HEC-18. HEC-18 covers all aspects of scour, including bridge design for scour, scour assessment, inspection procedures, and scour countermeasures. This circular presents a methodology for a detailed scour analysis, commonly referred to as Level 2 scour analysis, which is described in the following paragraphs (Richardson and Davis 1995).

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Three types of scour are addressed in the HEC-18 manual: (1) long-term aggradation and degradation, (2) contraction scour, and (3) local scour. Long-term aggradation and degradation, affected by either natural or man-made causes, refers to changes in streambed elevation over time. Contraction scour is primarily the result of channel constriction at a bridge crossing, where increased velocities scour the channel bed, but can also be caused by a change in local base-level elevation or flow around a bend. Typically, bridge approach abutments that block flow in the floodplain or extend out into the main channel are responsible for this scour type. Local scour is concentrated around piers, abutments, spurs, and embankments. Obstructions in the waterway impede and redirect flow, inducing the formation of vortices that accelerate the removal of bed material around the bases of obstructions. The cumulative sum of these scour types is the total scour (Richardson and Davis 1995).

Additionally, there are two components of both contraction scour and local scour: live-bed scour and clear-water scour. Live-bed scour occurs when bed material is transported from the upstream reach into the bridge crossing. Clear-water scour occurs when either no significant bed material is carried from the upstream reach into the downstream bridge reach or the material transported from the upstream reach is carried mostly in suspension through the bridge crossing to the downstream reach. HEC-18 provides the tools to evaluate both scenarios (Richardson and Davis 1995).

Although HEC-18 is widely used as the model to perform full scour analyses, there are two main problems with the methodology. First, in order to determine flow variables at a bridge, HEC-18 recommends the use of hydraulic modeling programs such as Water-Surface Profile Model (WSPRO) and HEC River Analysis System (HECRAS) (Richardson and Davis 1995). While these programs provide the some of the best estimates of flow variables, they are very costly and time consuming to perform. With large bridge inventories, states are reluctant to employ such time-intensive programs as part of their analyses for many of their bridges. Second, it is well documented that the HEC-18 equations can regularly give overly conservative scour depths. This may be due, among other things, to the inability of researchers to conduct tests on large-scale laboratory models. While it is better to have predictive methods that are conservative, excessive overestimation on a regular basis can increase costs to monitor, remediate, and even design and build bridges. These problems do not preclude the use of HEC-18 equations for scour evaluation, but rather should encourage DOTs to investigate other scour methodologies, in particular those that can generate similar results in a much shorter time period.

Connecticut Comparative Scour Analysis

The Connecticut Department of Transportation (CDOT) initially conducted its scour evaluation studies in general accordance with the aforementioned procedures. After performing Level 2 scour analyses on a few hundred bridges and faced with prohibitive costs and a large number of bridges remaining to be analyzed, CDOT looked to an alternative scour methodology to evaluate its bridges. The CDOT Hydraulic & Drainage Unit (H&D), along with the FHWA and consultants, developed a new, qualitative method that would provide NBIS Item 61, 71, and 113 codes for unanalyzed bridges without requiring full Level 2 scour analyses. This new method, called the comparative scour analysis, utilized the results of previous Level 2 scour analyses while generating time and cost savings (CHA 1998).

The comparative scour analysis is considered an intermediary step in the Comparison Methodology, the revised approach to scour assessment at bridges by CDOT. Its primary purpose is as a screening tool to provide NBIS code recommendations to as many previously unanalyzed bridges as possible during the early phases of the Comparison Methodology, thus eliminating them from further consideration and reducing the number of structures that ultimately receive more time-intensive scour analyses. It should be noted that the comparative scour analysis specifically does not calculate scour depths (CHA 1998).

To aid in the screening process, methodologies were established for collection of information during field visits and office reviews. Field reviews were performed by documenting field observations of site attributes related to the susceptibility of bridges to scour. These observations were quantified using fundamental scour parameters (FSPs) as a means of evaluating bridges according to the same criteria. Rating guidelines for the FSPs were provided to ensure consistent application of the documentation process. The existing 287 Level 2 bridges (i.e. those bridges that already received a full scour analysis) were evaluated and scored for the project according to the FSPs in order to verify that high ratings corresponded to low risk Item 113 ratings and low ratings reflected scour critical Item 113 ratings. Based upon the results, the ratings derived from the scour parameters were in good correlation with the Item 113 ratings for the Level 2 bridges, and the procedure was affirmed for field use (CHA 1998).

In order to justify the comparison of two bridges, one rated and the other unrated, primary and secondary criteria had to be met. Bridges that were already rated using the Level 2 analysis served as the group of rated bridges with which the unrated bridges would be compared. Primary criteria were considered to be Single vs. Multiple Span and Stream Character Category. Secondary criteria were listed as Estimated Stream Velocity, Foundation Type (at Abutments and Piers), Ratio of the Upstream Channel Width to the Width of the Channel Beneath the Bridge, and Angle of Attack. A valid comparison mandated that, at the very least, all primary criteria were met. The greater the number of secondary criteria met, the closer the similarity of the two bridges (CHA 1998).

The comparative scour analysis was designed so that the field team could make the comparison while at the site of the unanalyzed bridge. Accordingly, the field team was given a laptop, database information, and all other relevant information to assist their efforts. The comparison included not only similarities in primary and secondary criteria between the two bridges, but also incorporated review of FSP scores and office information for the sites along with a detailed look at the structural, hydraulic, and geotechnical characteristics of the Level 2 bridge. Based upon review of all this information and engineering judgment, the field team either recommended NBIS codes for the unrated bridge or recommended additional, more detailed scour analyses (CHA 1998).

Rapid-Estimation Method

Holnbeck and Parrett (1997) addressed the challenges of assessing bridge scour in a timely fashion in a report issued by the USGS and prepared in cooperation with the Montana DOT. As in other states, the large inventory of bridges in Montana, coupled with detailed scour analyses using hydraulic modeling programs, made it difficult to evaluate bridge scour at these sites in a short period of time. The rapid-estimation method was thus created for use as a quick screening tool to identify bridges susceptible to scour. It was also developed to provide results comparable to those from full scour analyses. Scour assessments at bridges using the rapid-estimation method were submitted for review to the Montana DOT, who then decided if a more thorough scour analysis was warranted for any bridge. Results from 122 detailed scour analyses in 10 states were used to justify its application across all regions. Holnbeck and Parrett (1997) emphasize that although this method was developed for use in Montana, it could be applied to other geographic regions.

The rapid-estimation method limits input parameters to those that can easily and quickly be measured in the field, provides reasonable estimates of scour depths without underestimating, and generates results in a period of hours, not days. Scour depth estimations and hydraulic variables are related through simplification of standard Level 2 scour equations and graphical plots. Envelope curves are used in these relations as means to ensure the overestimation, rather than underestimation, of scour depths. The only requirement of this method is knowledge of the discharge at the site, regardless of the recurrence interval corresponding to that flow. Other hydraulic variables are calculated in the field using graphs relating velocity to unit discharge and flow depth to velocity.

Bridge parameters are also determined in the field. Therefore, through the combination of limited site data and envelope curve relations, quick, yet reasonable estimates of scour depth at bridges are made in the field (Holnbeck and Parrett 1997).

GIS APPLICATION

Using a GIS as an assessment tool requires the assimilation of data from a variety of sources. For the purpose of the bridge scour assessment, the GIS is used to integrate and analyze the data. Three categories of data were needed for the GIS: bridges, gages and dams. In order to complete an analysis, the three data sets need to be assembled into coverages. The GIS allows for calculations based on all of the coverages as well as a means for spatially presenting the results of the analysis.

Of the several GIS platforms available, ArcView and ArcInfo (ESRI) were used for the application presented. It must be noted that the bridge scour analysis could be created using any of platform. The ESRI products are used only as one application example. The application was created as part of a study of the bridges in the six New England states For the New England Transportation Consortium (NETC 99-3). The aspects of creating the GIS application can be applied to bridge scour analysis anywhere.

Data Coverages

It is important to understand that the data needed for the bridge scour analysis must be compiled from many different sources. As mentioned earlier the sources are not all consistent and require some effort in coordinating the data. The data may exist in several different forms. Much of the data is still in plan form as many of the bridge designs were done prior to the digital age. Even many of the maps are in original graphical form. These data can be entered into coverages using digitizers or scanners. Fortunately much of geographical material has already been digitized into importable coverages. New England states have created websites for retrieval of the coverages (DiStasi 2001, Ho and DiStasi 2001). A list of the state GIS websites are given in Table 1.

There are numerous coverages available on these websites. The coverages that were used for this study (state boundaries, county boundaries, major river basins, and streams and rivers) were the ones that were used for the scour assessment. Statewide coverages were used when possible. This eliminated the need to tile coverages in order to properly characterize drainage basins and flood plains. Geopolitical boundaries are important to include as the identification of bridges is dependent on the political unit in which the bridge is located. Also, county boundaries were needed to interpret flood warning data as those warnings are generally given on a county by county basis. Stream and rive coverages were needed to confirm that bridges were in fact spanning a waterway.

In some instances, coverages needed to be modified. In particular, the watershed data was often given with too great of a specificity with respect to the density of bridges. Many of the small basins were merged into larger basins in order to be more appropriate for the analysis.

Bridge Coverages

The specific data on bridge design parameters are not generally given in the form of GIS coverages. These data need to be gleaned from other sources. It must be noted that the state DOT's have compiled extensive databases in the form of spreadsheets containing as much of the data. Even with these databases, many of the bridges are multiple listed, as there are shared jurisdictions (state highways, interstate highways, county roads, etc.).

The DOTs were asked to send bridge attributes they believed to be relevant for inclusion in the bridge scour database, including descriptors (town, county, id), bridge characteristics, stream characteristics, and rankings. There was some difficulty in obtaining the information from DOTs; complete bridge lists were received from Connecticut, Massachusetts, New Hampshire and Vermont. The two most important bridge attributes to collect are a unique bridge id and a bridge location. Any and all other attributes can easily be added or modified at a later time. Emphasis was placed upon including attributes pertinent to bridge scour equations as well as parameters that could be manually queried by the DOTs that would help identify and prioritize bridges generally more susceptible to scour, such as foundation type, scour indices, critical flow events, countermeasures installed (if any), and average daily traffic (ADT). The ability to see the locations of these bridges and use attributes to identify bridges most susceptible to scour during a storm event are vital to earlier and better preparation and response by DOTs and emergency management agencies. Attributes may also be queried to identify trends in infrastructure weakness as well as establish prioritization for bridge remediation.

Once the bridges were entered into the GIS, a cursory check was made to ensure that the sites fell within the state boundaries. In cases where they didn't, the coordinates were checked, and if a discrepancy existed, the DOT was notified and a correction was made.

Stream and Rain Gage Data

Although real-time hydrological data are an important component to this project, the data are not very useful without spatial knowledge of the gage locations. Whether the gage data are monitored throughout the course of a storm or forecast offices provide estimates of precipitation totals or river stages at various gage locations, the user must be aware of gage sites in relation to scour susceptible bridges and dams. Therefore, it was crucial that locations of all active real-time rain and stream gages were identified and entered into a GIS for each state.

An extensive search of the Internet revealed no comprehensive website that included all rain and stream gage networks. Websites with information regarding gage networks typically had their own GIS map showing gage locations, but the map was usually not available to download. The multiple coordinate systems and map formats used by various agencies on their websites also posed difficulties for integrating them within each state GIS. It was thus easier to extract the gage locations and attributes manually and then insert them as new GIS coverages.

Relevant stream gage attributes included general descriptors as well as drainage area into gage. Warning and/or flood thresholds were available for some gages, but were not included as part of the gage attributes. Rain gage attributes were similar to the ones for stream gages, but gage elevation was also added as a parameter.

Dams

It was decided that it would be also useful to incorporate the locations of dams into the GIS, due to their potential impact on the accuracy of stream gages during a significant storm event. This would serve dual purposes: (1) identify gages with regulated flows and (2) aid in the placement of future gages. While thousands of dams have been constructed in New England, only a fraction of these significantly affect the stream gages. The National Inventory of Dams, which is maintained by the Army Corps of Engineers, is available online and contains database information on thousands of dams nationwide ("National Inventory of Dams"). Due to the large number of dams in each state and that fact that no one dam attribute directly impacts bridge scour, all of the dams in the inventory were incorporated into the GIS for the time being. It is better to have too much information than too little and the data can easily be queried to eliminate dams from consideration.

Prediction of Flood Levels

In order to conduct a prioritization of the bridges, archival data needs to be compiled in an accessible and modifiable format. A solution to this is the creation of "gage tables" and "scour tables", which, when used in conjunction with real-time gage data, allow the user to assess scour conditions at bridges in real-time. The use of these tables can be used both as a comparison tool to evaluate the scour potential in real time and to consider the recurrence of scour critical events. Depths could be estimated and catalogued in a database in advance based upon predicted discharges for several return periods. The predicted scour occurring in "real-time" would then be verified using real-time data from nearby gages. Scour depth estimates for bridges will be predetermined and stored in tabular format for a number of flood flow events along with the bridges' scour critical events.

These "gage tables" and "scour tables" would be compiled from existing gage and bridge attributes already stored within the GIS. The intent of these "tables" is to summarize relevant scour attributes for presentation purposes. The user could look at these tables without pulling up extraneous attributes that overall may be important to the gage or bridge, but unimportant within the context of these "tables." These "tables" are of course subject to modification by DOTs.

"Gage tables" would be compiled from statistical analyses of historical gage data or from streamflow statistics made available by websites such as StreamStats. These data would be stored within each gage's attributes in the GIS. "Gage tables" should at least contain various flow return intervals and their corresponding discharge values. "Scour tables" can easily be generated for bridges that have already undergone a full Level 2 analysis in which scour depths were calculated for certain flow events. These "tables" should include various flow return intervals along with corresponding discharge values, predicted scour depths, and determination if the event is scour critical. Many bridges did not receive these intensive analyses, however, meaning scour depths and scour critical events would need to be calculated for hundreds of bridges. This task is made difficult by the cumbersome nature of existing analyses, especially since they require the use of hydraulic modeling programs. A tool like the rapid-estimation method, though, would allow DOTs to quickly and reasonably estimate scour depths at bridges for flow events of different recurrence intervals. Discharges at bridges could be estimated using a variety of methods as described earlier and the rapid-estimation method would again be used to generate hydraulic variables. Figure 1 presents an envelope curve for estimation of pier scour using the rapid-estimation method. Pier scour can be calculated using this figure along with knowledge of bridge geometry and hydraulic variables, both of which are determined in the field using this method. Even if scour depths are not calculated using the rapid-estimation method, the method can still be used to quickly estimate flow variables for input into different scour algorithms. Regardless of how "scour tables" are created, it is emphasized that if these tables are not available for all bridges, then the potential of prioritization is limited.

Figure 2 presents a map of Connecticut bridges displayed according to their scour critical event determined using HEC-18. The user, though, may want to evaluate the bridges using another equation within the model manager. With equation parameters already stored in the bridge attributes (including flow variables), scour depths can be recalculated (and "scour tables" revised) using the new equation. Regardless of the scour equation, though, the scour depth that would cause factors of safety to fall below acceptable limits would have to be known for each structure. After applying the new equation, a new map would display the same bridges as the first, but the color or symbol scheme for the bridges would be different. The versatility of the model enables discretion to be used, permitting scour to be evaluated a number of different ways and allowing for a more complete analysis.

Analyses should not be limited to comparing bridges using the same equation, though, because equations may be better suited for application to certain bridges based upon the bridges' attributes. The NH USGS report demonstrated that the New York 1996 equation showed some promise as a predictive scour algorithm, but results were largely sensitive to decreases in bed material particle-size (Boehmler and Olimpio, p. 23, 2000). With this knowledge, the user could query all bridges with a minimum median bed particle size and evaluate them using the 1996 New York equation and then analyze the remaining bridges with a smaller median bed particle size using a different equation.

Engineering judgment should always be part of bridge scour analysis. Decisions should not be made solely using quantitative measures. The "gage tables" and "scour tables" are not intended to give exact scour conditions at any given time, but rather provide guidance as to the magnitude of the event and facilitate assessment of scour at bridges in real-time, particularly for prioritization purposes. The importance of engineering judgment is inherent in the SDSS, which allows the user to perform tasks at their discretion.

CONCLUSION

It is important to consider that the prioritization of bridges susceptible to scour can be reasonably accomplished using a GIS scheme. This requires that an understanding of the limited data about the as-built conditions of the bridges is needed. Also, it is important to incorporate appropriate information on stream flow and gage measurements to properly assess the return periods of flood levels.

The combination of the stream gage data and the bridge scour data can be effectively used to make predictions with respect to return periods of scour events. Lower return period will result in higher scour hazard. Presentation of the return periods can be effectively made using the GIS mapping capabilities.

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Table 1. State GIS websites (DiStasi, 2001, Ho and DiStasi 2001).

State	URL Address
Connecticut	http://magic.lib.uconn.edu/
Maine	http://apollo.ogis.state.me.us/
Massachusetts	http://www.state.ma.us/mgis/massgis.htm
New Hampshire	http://www.granit.sr.unh.edu/
Rhode Island	http://www.edc.uri.edu/rigis/
Vermont	http://geo-vt.uvm.edu/

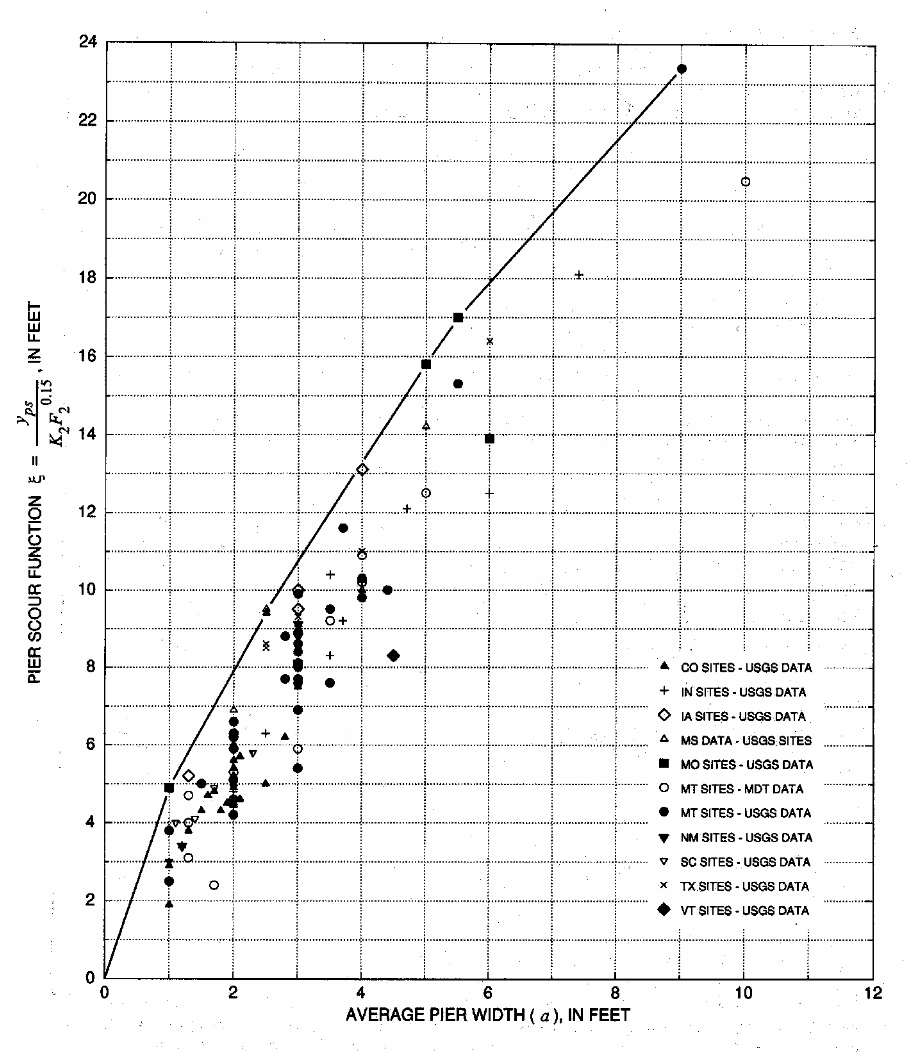

Figure 1. Envelope curve for estimation of pier scour (from Holnbeck and Parrett 1997).

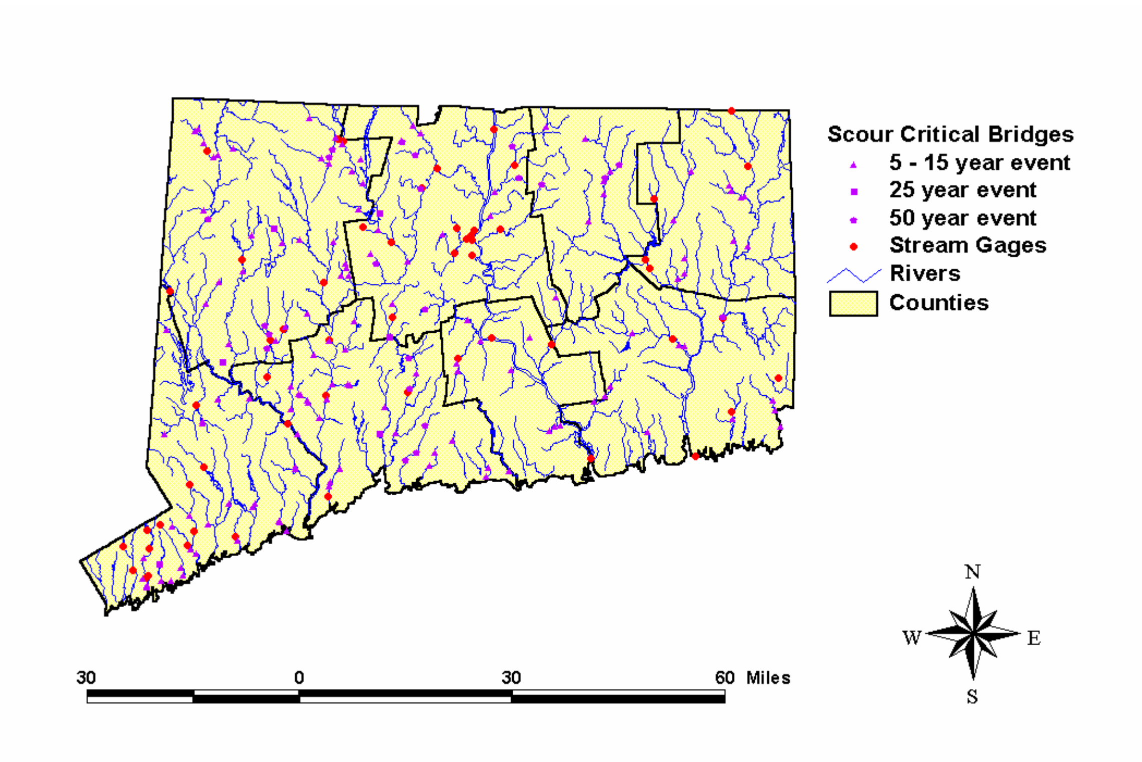

Figure 2. Scour critical bridges in CT (50-year event or smaller).