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Evaluation of SRICOS Method on Cohesive Soils in South Dakota

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Final Report

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November 2008

DISCLAIMER

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16. Abstract
The SRICOS (**S**cour **R**ates **I**n **CO**hesive **S**oil) method had been proposed as an alternative design methodology for predicting scour at bridges founded in cohesive soils. As the new method can produce substantial savings in bridge construction costs at cohesive soil sites, it is important that SDDOT evaluates the method carefully for use in bridge design. This research project compared the predictions of the SRICOS method for pier scour with measured scour at three bridge sites in South Dakota and examined the technical issues involved in using the method.

The research began with an assessment of the SRICOS method and a survey of current practice in evaluating bridges for scour used by other State DOTs. Three bridge sites in South Dakota were selected to evaluate the method for pier scour. Subsurface exploration, laboratory testing, hydraulic modeling, and hydrologic analysis were performed for each site to generate the inputs for computing scour using the SRICOS method. The computed scour depths were compared to the measured scour obtained by the USGS in 1991-1993 when a number of large floods occurred at the study sites. To provide a scale for the comparison, a sensitivity analysis was performed for each site to determine the sensitivity in the computed scour depth to the input parameters. The site-specific sensitivity analyses were complemented by a non site-specific sensitivity analysis to identify and rank the critical input parameters. A method to use the SRICOS method to predict bridge scour in watersheds where streamflow records are not available was proposed.

This report recommends that SDDOT: (1) uses the SRICOS method as a supporting tool in evaluating bridges for scour, (2) continues to monitor current and future research to observe new improvements, (3) conducts workshops to train design engineers in using the method; (4) constructs a testing equipment to measure soil erodibility; (5) establishes a procedure for collecting scour data immediately after major floods to verify future improvements; and (6) conducts research to improve predictions of hydraulics of bridge waterways and the effect of large floods on time rate of scour.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

INTRODUCTION

This research project evaluated the SRICOS method, which predicts bridge scour in cohesive soils (silts and clays), by comparing its predictions with measured scour at three bridge sites in South Dakota. Current methods for predicting bridge scour were developed for non-cohesive soils (sands and gravels) and predict the maximum or equilibrium scour depth at a bridge site produced by a single design flood. The new method is expected to predict scour depths less than the maximum predicted by existing methods because cohesive soils scour more slowly than non-cohesive soils and the duration of flooding events in many South Dakota streams is not of sufficient length to establish equilibrium conditions. However, predictions from the SRICOS method have not been compared extensively with measured scour in the field for verification of accuracy. Furthermore, the method requires a hydrograph as one of the inputs, which may not be available for small watersheds and un-gauged streams. These and other technical issues must be addressed before the new method can be adopted for designing bridge pier foundations to account for scour in cohesive soils.

OBJECTIVES AND SCOPE OF RESEARCH PROJECT

This research project had three primary objectives. The first objective was to evaluate the SRICOS method for predicting scour at bridge sites in South Dakota. Three field study sites with scour data and flow measurements were selected for detailed evaluation. Second, it was unclear how sensitive the scour predictions from the SRICOS method were to the inputs. Therefore, the research team had conducted both site-specific and non site-specific sensitivity analyses to determine the critical input parameters to the SRICOS method. Third, modifications are needed to make the SRICOS method more efficient to use in design for small watersheds, where streamflow records are often lacking. This research project also examined the technical issues involved in using the SRICOS method and identified the technical support, resources and future research that are needed to successfully implement the method.

CONTRIBUTIONS/POTENTIAL APPLICATIONS OF RESEARCH

At bridge sites with highly scour resistant cohesive soils, it is expected that the predicted scour depth from the SRICOS method would be substantially less than the maximum or equilibrium scour depth predicted by current methods which were developed for non-cohesive soils. This means that footing and pile depths will not need to be as deep as is currently designed. Consequently, substantial savings in bridge construction costs may result and this can be measured by dollars saved in SDDOT projects.

THE APPROACH

A comprehensive review of the SRICOS method was completed. A list of specific questions on bridge scour was developed to form a questionnaire for the project. Eleven State DOTs were contacted through telephone and asked the questions on the questionnaire. The survey gave the research team an understanding of the current practice used by design engineers in evaluating bridges for scour.

Archival data and engineering documents on 12 bridge sites in South Dakota were obtained from SDDOT and USGS and carefully studied to select three bridge sites for evaluating the SRICOS method. The research team visited six of the bridge sites that met the minimum selection criteria. The Big Sioux River Bridge near Flandreau on SD Highway No. 13, the Split Rock Creek Bridges near Brandon on Interstate 90 eastbound and westbound, and the White River Bridge near Presho on US Highway No. 183 were proposed and approved by the SDDOT for use in evaluating the SRICOS method. The period of evaluation was 1991 to 1993 when flow and scour measurements were collected by the USGS at the bridge sites during several flooding events.

Subsurface explorations were conducted at the three study sites. At each site, drilling was conducted at one or more locations in the bridge abutments on opposite sides of the channel. Continuous sampling with Standard Penetration Test (SPT) was performed from the ground elevation to the foundation elevation to delineate the soil stratigraphy at the bridge site. Thin wall (Shelby) tube samples were collected at selected depths from each boring. The soil samples were tested in the Geotechnical Laboratory at South Dakota State University (SDSU) to determine the basic index and geotechnical engineering properties of the site soils. The research team also travelled to St. Paul, Minnesota to conduct EFA (Erosion Function Apparatus) testing at the Minnesota Department of Transportation (MNDOT) Materials Laboratory. Additional EFA testing was conducted by researchers at Texas A&M University (TAMU) to verify the results of EFA tests conducted by SDSU.

Numerical modeling was conducted using the one-dimensional River Analysis System HEC-RAS to compute the flow conditions at the study sites in 1991 to 1993, using either recorded or estimated hydrographs. Flow data from stream gauging performed by the USGS were used to calibrate the numerical model to ensure reliable results. Rating curves were generated from numerical simulations and used with recorded or estimated hydrographs to compute the water surface elevation and approach flow velocity at each site to provide the hydraulic inputs to the SRICOS method.

The SRICOS method was programmed in the FORTRAN environment and simulations were conducted for a total of five bridge piers from the three study sites. The results were compared with the measured scour in 1991 to 1993 to evaluate the method. A sensitivity analysis was conducted for each site to determine the sensitivity in the computed scour depths due to variation in the inputs in order to provide a scale for comparing the computed and measured scour. In parallel, a non site-specific sensitivity analysis was performed to assess the effects of change in the individual model input parameters in the SRICOS method on the model predictions. The input parameters were ranked on the basis of their influence on the output and the critical input parameters were identified.

A literature review on the techniques for constructing synthetic hydrographs for gauged and un-gauged watersheds was conducted. SRICOS simulations were performed to study the effect of the temporal structure of the hydrograph on the time rate of scour. A procedure for using the SRICOS method to predict bridge scour at un-gauged sites was proposed. The procedure considers that a few large flooding events contribute most of the scour. The hydrographs of these floods can then be constructed using methods that have been developed for rainfall-runoff analysis. The level of detail in the analysis will depend on the hydrologic data and resources available. The procedure was illustrated using the Split Rock Creek Bridges as an example.

FINDINGS AND RECOMMENDATIONS

The SRICOS method uses site-specific testing of soil erosion rates to predict bridge scour depth as a function of time. This approach represents a significant advance over existing methods which only predict the maximum or equilibrium scour depth, and which do not account for the erodibility of the site soils. The SRICOS method is not currently used by State DOTs to evaluate bridges for scour. There are several reasons for this. First, there are concerns about the reliability of the method; the method has only been tested for a few bridge sites in the United States. Second, the new method requires additional equipment for measuring soil erosion rates that is not available to most DOTs. Third, the SRICOS method requires more expertise in geotechnical, hydraulic, and hydrologic analyses than the current methods. Therefore, additional training of personnel is required. Finally, the cost, time, and amount of input data increase significantly with the new method. Each of these issues is addressed below.

The research team found that, at all three study sites, the SRICOS method was able to predict pier scour that was comparable to the observed scour by using reasonable values for the input parameters. However, the predicted scour depth was very sensitive to the critical shear stress, slope of the erosion rate versus shear curve, approach flow velocity, and flow angle of attack (for long piers). In addition, as is expected with any bridge site, there was large variation in the subsurface lithology due to the depositional environment. Hence, careful delineation of the soil stratigraphy at the bridge site and improving the accuracy of EFA testing and bridge hydraulics analysis will be critical when using the new method. This report recommends that SDDOT uses the SRICOS method initially as a supporting tool in evaluating bridges for scour. As SDDOT personnel become more familiar with the new method, there would be confidence in using the method in design. Guidelines were proposed in using the SRICOS method given knowledge of its current limitations.

The research team found that there was high uncertainty in the measured erosion rate versus shear stress curve obtained using a commercial erosion function apparatus. With the current design, the applied bed shear stress cannot be estimated reliably, leading to large uncertainties in the critical shear stress and slope of the erosion function. The causes of this problem are relatively well understood, and improvements had been made by others in building their own erosion function apparatus. In order to use the SRICOS method, it is necessary to determine the erodibility of the site soils. This report recommends that SDDOT works with SDSU to modify an existing open-channel flume for EFA testing. The knowledge and skill required to do this correctly is available and there are substantial savings and technical advantages to design and build one's own erosion function apparatus for research. In addition to bridge scour, the apparatus should also be useful in other projects such as assessing channel stability and soil erosion.

This report recommends that SDDOT works with South Dakota State University to conduct some workshops to train SDDOT personnel and its consultants on the use of the SRICOS method. These workshops should cover all the important elements of the method including subsurface exploration, laboratory testing, hydraulic and hydrologic analysis, and computing the scour depth versus time curve. New workshops can be organized when future improvements to the method are available. The report also recommends that SDDOT becomes an active partner with the FHWA and other State DOTs in developing the SRICOS method. This will include supporting and engaging in research to improve the method, training and continuing education of personnel through workshops and seminars, acquiring the resources needed to implement the method, and promoting the use of the method in evaluating bridges for scour.

This report lists three areas of research which SDDOT should pursue, in the near future, to make the SRICOS method more reliable and more efficient to use. They are: (1) establishing an organizational structure to collect scour data and assess scour damages after major floods to verify the SRICOS method against additional case studies; (2) improving predictions of hydraulics of bridge waterways to minimize the uncertainties in the hydraulic inputs; (3) understanding the effects of temporal structure of hydrograph and soil types on time rate of scour to develop easier methods for generating synthetic hydrographs for small watersheds and un-gauged sites where streamflow records are lacking.

PROBLEM DESCRIPTION

Scour is the erosive action of water which excavates soils from stream beds and banks. The types of scour that can occur at a bridge site are general scour, contraction scour and local scour. General scour is associated with natural processes of river flow irrespective of the presence of the bridge, whereas contraction scour and local scour are directly attributed to the presence of the bridge. Contraction scour results from river channel blockage at the bridge site, and is characterized by a general lowering in the local bed elevation. Local scour is caused by the three-dimensional turbulent flow around the bridge structure, and is characterized by the formation of scour holes around the bridge foundation. This research project is concerned only with local scour around bridge piers.

The current procedure used by South Dakota Department of Transportation (SDDOT) for estimating scour at bridges is given in the United States Federal Highway Administration (FHWA) document entitled "Evaluating Scour at Bridges," Hydraulics Engineering Circular No.18 (HEC-18; Richardson and Davis, 2001). The scour prediction equations in HEC-18 were developed for non-cohesive soils (sands and gravels) and predict the maximum or equilibrium scour at the bridge site based on a single flood event. However, many bridges in South Dakota are founded on cohesive soils consisting of silts and clays (Niehus, 1996). Since silts and clays scour more slowly than sands and gravels, using the scour equations in HEC-18 may over predict the extent of scour. This may result in over design of new bridge foundations or installation of unnecessary scour countermeasures at existing bridges. With reliable methods for predicting scour in cohesive soils, SDDOT could potentially save substantial dollars in construction costs for bridges built over waterways.

Using the results of flume tests and numerical modeling, the SRICOS (**S**cour **R**ate **I**n **CO**hesive **S**oils) method had been developed by researchers from Texas A&M University (TAMU) to predict the rate of scour as well as the maximum scours depth at bridges. The advantage of the SRICOS method over the HEC-18 equations is its ability to predict the rate of scour while taking into account the measured erosion rates of the site soils. The SRICOS method is applicable to cohesive soils as well as non-cohesive soils, and it can be adapted to predict scour associated with a hydrograph. Thus, the new technique has the potential to result in substantial saving in construction costs if the expected scour over the life time of the bridge is considerably less than the equilibrium scour. The primary limitation of the method at this time is the limited extent of verification in the field. The SRICOS method had only been tested for local and contraction scour at a small number of bridge sites in the United States (e.g., Briaud et al., 2001b, Curry et al., 2003, and Ghelardi, 2004). To apply the method in SDDOT design, there is a critical need to verify the method with specific sites and soils in South Dakota. There are also practical issues associated with using the method. One of the inputs of the SRICOS method is the discharge versus time curve or hydrograph at the bridge site. However, detailed streamflow data are often lacking in small watersheds. Hence, guidelines need to be developed on use of the method for small watersheds and un-gauged streams.

OBJECTIVES

The objectives of this research project were to:

1. DETERMINE IF THE SCOUR PREDICTIONS FROM THE METHOD ARE COMPARABLE WITH EXISTING SCOUR DATA IN COHESIVE SOILS IN SOUTH DAKOTA.

This objective was accomplished by working with the SDDOT and the South Dakota District of the United States Geological Survey (USGS) to select three bridge sites in South Dakota for evaluation of the SRICOS method. A comprehensive review of the SRICOS method was completed. Existing bridge scour records were searched and site visits were conducted to select three bridge sites that met the requirements necessary for evaluating the method. The Big Sioux River Bridge near Flandreau on Highway No. 13, the Split Rock Creek Bridges near Brandon on Interstate 90 eastbound and westbound, and the White River Bridge near Presho on US Highway No. 183 were selected for study. Drilling and sampling were conducted at each bridge site to collect Standard Penetration Test (SPT) and thin wall (Shelby) tube samples for erosion rate testing and soil analysis as well as for delineating the existing soil conditions at each site. Flow discharge data were either obtained from the USGS website if a streamflow gauging station existed at or near the bridge site, or estimated by hydrologic simulation and streamflow synthesis if no records were available. The flow discharge data and surveyed channel cross sections were entered into the Hydrologic Engineering Centers River Analysis System (HEC-RAS) to compute the water surface elevations and approach flow velocities at the bridge sites. The results of erosion rate tests and HEC-RAS analyses were entered into the SRICOS program to compute the scour depth versus time curves at a total of five bridge piers from the three study sites. The predicted final scour depths were compared to the observed scour depths to evaluate the SRICOS method. A sensitivity analysis was performed to provide a scale for the comparison.

2. Conduct a sensitivity analysis of the SRICOS program and identify the critical input parameters.

In addition to the site-specific sensitivity analyses, a non site-specific sensitivity analysis of the SRICOS method was performed for pier scour. The non site-specific analysis was focused towards model sensitivity. Computer programs were developed using MATLAB codes for batch processing of the method. The sources of uncertainty were identified. Numerical testing was conducted to quantify the effects of uncertainty in the input parameters on the predicted final scour depth and to rank the critical input parameters. Recommendations were developed on how to reduce uncertainties in scour prediction.

3. Provide guidelines on use of SRICOS method for small watersheds and un-gauged streams.

Techniques for generating future hydrographs for scour prediction using the SRICOS method were reviewed. Using approximately 25 years of streamflow records at the Big Sioux River and Split Rock Creek sites, the effects of the temporal structure of streamflow sequences on predicted scour history and final scour depth were investigated. A method for predicting final scour depth at un-gauged sites was proposed. The method considers that the bridge will be designed to withstand scour produced by a number of large floods. Inputs to the method include the peak flow and flood duration of the design floods. To use the method, a unit hydrograph is first selected. Then, the peak flow is estimated by using regional regression equations or frequency analysis. The surface runoff is estimated using rainfall atlas and the SCS (Soil Conservation Service) curve number. Once the peak flow and surface runoff are known, the flood duration can be calculated. The method was applied to the Split Rock Creek Bridges to predict the final scour depth produced by a sequence of rectangular or triangular floods.

RESEARCH TASKS

The research project consisted of the following twelve specific tasks:

1. CONDUCT A LITERATURE SEARCH WHICH WILL INCLUDE FLOOD-FREQUENCY PREDICTIONS FOR SMALL WATERSHEDS AND UN-GAUGED STREAMS AND COMPARE THE RESULTS WITH OTHER STATES AS THEY RELATE TO USE OF THE SRICOS METHOD TO EVALUATE BRIDGE SCOUR. AT A MINIMUM THIS WILL INCLUDE SURROUNDING STATES.

A general literature review on bridge scour in cohesive soils and the techniques for estimating peak-flow magnitude and frequency for small watersheds and un-gauged streams was conducted. A list of specific questions was developed to form a questionnaire for the project. Five neighboring State DOTs (Minnesota, Montana, Nebraska, North Dakota, and Wyoming) and six other State DOTs (Alabama, California, Illinois, Iowa, Maryland, and Texas) were contacted via telephone and asked the questions on the questionnaire. A comprehensive review of the SRICOS method is presented in Appendix A. The questionnaire and a summary of the telephone survey are presented in Appendix B.

2. THROUGH COLLABORATION WITH SDDOT AND USGS IDENTIFY THREE SITES FOR VERIFICATION OF THE SRICOS METHOD.

The final report of a prior research project on scour assessments for selected bridge sites in South Dakota (Niehus, 1996) was reviewed. A preliminary evaluation was conducted on 12 bridge sites based on the information provided in this report. Six of the bridge sites met the minimum selection criteria. Individual reports for these six sites and other pertinent information including bridge plans, borehole data, and available flow and scour measurements were obtained from the SDDOT office in Pierre and the USGS district office in Huron for detailed study. Site visits were conducted to become familiar with each site and to depict site conditions (e.g., apparent flow directions and concentrations, geomorphic characteristics, access to drilling) important to the project. The Big Sioux River Bridge near Flandreau on Highway No. 13, the Split Rock Creek Bridges near Brandon on Interstate 90 eastbound and westbound, and the White River Bridge near Presho on US Highway No. 183 were proposed and accepted by the SDDOT for use in evaluating the SRICOS method. The period of evaluation was 1991 to 1993. A summary of the site evaluation is presented in Appendix C.

3. MEET WITH THE TECHNICAL PANEL TO REVIEW PROJECT SCOPE, DISCUSS ISSUES, AND PRESENT TENTATIVE WORK PLAN.

The first meeting with the technical panel was held on April 24, 2007 in the SDDOT Building in Pierre. The researchers gave a review of the SRICOS method and presented a summary of the telephone interview of State DOTs. The criteria for bridge site selection and potential bridge sites for evaluating the SRICOS method were presented, and work plan for the coming months was discussed. The technical panel approved using the Big Sioux River Bridge and Split Rock Creek Bridges as study sites. The White River Bridge was approved after a site visit was conducted in August.

4. CONDUCT SITE INVESTIGATIONS, AND COLLECT A MINIMUM OF FOUR SHELBY TUBE SOIL SAMPLES PER SITE, AND COMPLETE DRILLING LOG OF SITES IDENTIFIED IN TASK 3. ALL DATA COLLECTED WILL BE INCLUDED IN THE FINAL REPORT. CONTINUOUS SAMPLING WILL BE CONDUCTED FROM FLOW LINE DOWN TO FOUNDATION ELEVATION.

Subsurface explorations were conducted in June and July, respectively, for the Big Sioux River Bridge and Split Rock Creek Bridge sites, and in October for the White River Bridge site. At each bridge site, drilling was conducted at one or more locations on the bridge abutment on opposite sides of the channel as close as practically possible to the bridge pier(s) to be evaluated. Sampling with Standard Penetration Test (SPT) was performed from the ground elevation to the foundation elevation. Thin wall (Shelby) tube samples were collected at selected depths from each drill hole. The drilling and sampling was performed by a drilling company. The researchers logged the drill holes and took possession of the soil samples for soil analysis and EFA testing. SDDOT provided traffic control during drilling. The geotechnical data are presented in Appendix D.

5. Conduct Erosion Function Apparatus (EFA) testing on Shelby tube samples (minimum of four samples per site), grain size analysis, and Atterberg limits as required. Report soil classification with AASHTO standard designation.

A laboratory testing program was performed at South Dakota State University (SDSU) to evaluate the basic index and geotechnical engineering properties of the site soils. Both disturbed and relatively undisturbed samples were tested. The tests performed included soil classification, water content determinations, Atterberg limits (AL), grain size analysis (GS), and 200-wash. The results of standard soil tests are presented in Appendix D.

Four separate trips were made to the Minnesota Department of Department (MNDOT) Materials Laboratory in St. Paul, Minnesota to conduct erosion rate testing. Three thin wall (Shelby) tube samples from the Big Sioux River Bridge, five samples from the Split Rock Creek Bridges, and four samples from the White River Bridges were tested in an Erosion Function Apparatus (EFA) to obtain the erosion rate versus shear stress curves. Two additional thin wall tube soil samples from duplicate soil locations collected from the White River Bridge were sent to Texas A&M University for EFA testing to assess the repeatability of the EFA tests conducted by SDSU. The results of EFA tests are presented in Appendix E.

6. Obtain hydrologic data (estimate if none existing) and run Hydrologic Engineering Centers River Analysis System (HEC-RAS) on data to obtain flow velocity at bridge pier sites identified in Task 2.

Hydraulic analyses were conducted for the study sites using HEC-RAS. The computed results were compared with field measurements obtained by the USGS in 1991 to 1993 to calibrate the computer models. The water surface elevations and approach flow velocities at each bridge site were computed for a range of flow discharges to generate the rating curves. Both hourly and daily mean flow data were available at the Big Sioux River site. Only daily mean flow data were available at the White River site. Continuous discharge record was not available at the Split Rock Creek sites in 1991 to 1993. Two different methods were used to hind-cast the hydrograph at the Split Rock Creek sites for a major flood in May 1993. The first method used the recorded hydrograph from the Skunk Creek gauging station near Sioux Falls, which had similar hydrologic characteristics as the Split Rock Creek sites. After removing the base flow, the hourly mean flow data from the Skunk Creek site were scaled up so that the peak flow matched the measured peak flow from crest-stage partial records at the Split Rock Creek sites. The second method used the Soil Conservation Service (SCS) Dimensionless Unit Hydrograph to construct a synthetic hydrograph for the Split Rock Creek sites. The hydrologic and hydraulic analyses for the Big Sioux River Bridge, Split Rock Creek Bridges, and White River Bridge are presented in Appendices F, G and H, respectively.

7. Run SRICOS program on data obtained from previous tasks and sites identified in Task 2. Compare these scour predictions with existing scour data.

The SRICOS methodology was programmed in the FORTRAN environment based on the scour equations documented in NCHRP Report 516 (Briaud et al., 2004). Trial runs were conducted and checked against the results obtained using the SRICOS program downloaded from TAMU (http://ceprofs.tamu.edu/briaud/SRICOS-EFA.htm). SRICOS simulations were conducted on two bridge piers at the Big Sioux River site, one pier at the Split Rock Creek sites, and two piers at the White River site. The simulations were conducted using our own FORTRAN codes because we implemented the correction factors for flow depth, flow angle of attack and pier spacing differently from the TAMU program; this is explained in Appendix A. The predicted final scour depths were compared to the scour depths measured by the USGS in 1992-1993. A sensitivity analysis was conducted for each site to determine the variation in the scour depth predictions due to variations in the input parameters. The results of SRICOS simulations for the three study sites are presented in Appendices F, G and H, respectively.

8. CONDUCT SENSITIVITY ANALYSIS ON DATA FROM TASK 7 AND IDENTIFY CRITICAL INPUT PARAMETERS IN THE SRICOS PROGRAM.

The SRICOS methodology was programmed in the MATLAB environment for batch processing of the method for a non site-specific sensitivity analysis. Sensitivity analyses were conducted to assess the effects of change in individual model input parameters on model predictions. This was done by varying one parameter at a time and recording the associated changes in model response. The input parameters were ranked on the basis of their influence on or contribution to the variability in the model output and the critical input parameters were identified and ranked. The sensitivity analysis was conducted on pier scour only. This analysis differed from the sensitivity analysis described in Task 7 in that it was focused towards model sensitivity and not site sensitivity. The results of non site-specific sensitivity analysis are presented in Appendix I.

9. Meet with technical panel to review drilling information, soil testing results, SRICOS predictions, and other significant data that has been collected to date.

The research team held a second meeting with the technical panel in Pierre on November 27, 2007 and a third meeting on May 28, 2008 to report on work completed and to review the work plan.

10. Provide guidance on use of SRICOS Method for predicting bridge scour in small watersheds and un-gauged streams.

Existing methods for constructing hydrographs for gauged and un-gauged watersheds were reviewed. The data requirements for using these methods were discussed. A simple method for using the SRICOS method to predict scour in un-gauged streams was developed. Instead of generating a long hydrograph for the design service life of the bridge, the new method considers that a few large floods contribute most of the scour. The hydrographs of these large floods can be constructed using methods that have been developed for rainfall-runoff analysis. The choice of which method to use will depend on the field data and resources available. The simplest approach may adopt a rectangular or triangular hydrograph and use the regional regression equations and rainfall atlas to estimate the peak flow and duration of the hydrograph. This approach was used to predict the final scour depth at the Split Rock Creek site for a sequence of 100-year floods. A literature survey on hydrograph analysis for gauged and un-gauged watersheds and details of the proposed method are presented in Appendix J.

11. Prepare a final report and executive summary of the prior research, research methodology, findings, conclusions and recommendations.

A draft final report was submitted for review by the SDDOT in November 2008.

12. MAKE AN EXECUTIVE PRESENTATION TO THE SDDOT RESEARCH REVIEW BOARD AT THE CONCLUSION OF THE PROJECT.

An executive presentation of the research was presented to the Research Review Board in Pierre on November 18, 2008. An extended presentation was made to the technical panel in the afternoon after the Research Review Board meeting.

FINDINGS AND CONCLUSIONS

REVIEW OF SRICOS METHOD

Using the results of flume tests and numerical modeling, the SRICOS-EFA method had been developed by researchers at Texas A&M University to predict the time rate of scour as well as the maximum scour depth at bridges. The SRICOS method is applicable to both cohesive and non-cohesive soils; it uses site-specific measurements to quantify soil erosion rates. The method can be adapted to predict the scour history produced by a hydrograph and in a multi-layer soil stratigraphy. The basic approach can be modified to predict pier, contraction, and abutment scour. Individual elements of the method can be updated and improved as new research results become available. Therefore, the SRICOS method represents a significant advance over existing methods for bridge scour predictions.

In applying the SRICOS method to predict scour at full-scale bridges, the limitations of the equations must be recognized. The regression equations used for calculating the maximum pier scour depth z_{max} and the maximum initial bed shear stress τ_{max} were developed based on small-scale flume tests in clays, primarily porcelain, and numerical modeling. The equation for z_{max} predicts maximum scour depths similar to those given by the HEC-18 equation, and should provide a conservative estimate when applied to other cohesive soils. However, the flume tests and numerical modeling were conducted at laboratory scales and covered only a relatively small range of flow and pier parameter values. Therefore, using these regression equations on prototype bridges may apply the equations outside the range of flow conditions for which they were developed.

The regression equations for contraction scour have some of the same limitations as those for pier scour. They are based on flume tests in porcelain clay and it is unclear how well the equations would perform with other soil types. The flume tests and numerical simulations were carried out for a rectangular channel with vertical side walls over a relatively small range of flow conditions.

The Erosion Function Apparatus is one of the few devices available for measuring soil erosion rates. With an EFA, soil samples can be collected with a thin wall tube at specified depths and tested relatively undisturbed in the EFA over a wide range of applied shear stress. The current design, however, is not particularly accurate because the operator has to monitor the erosion by eyes and determine when to advance the soil sample. Furthermore, the applied shear stress is calculated using equations developed for pipe flows and may not correctly represent the erosive action of the water on the test sample. Hence, there are large uncertainties in the estimated shear stress and measured erosion rates. These shortcomings, however, are not insurmountable and the EFA remains a valuable tool for obtaining site-specific information on soil erosion rates.

The pier scour predictions from the SRICOS method had been compared to field measurements at only a small number of bridge sites in the United States. These results were inconclusive for several reasons. Some of the sites investigated did not have surveyed channel cross sections upstream and downstream of the bridges, which were needed to accurately compute the water surface elevation and approach flow velocity at the bridge. Also, it is not known how well a one-dimensional model like HEC-RAS predicted the water depth and approach flow velocity at these sites, since there were no velocity measurements for comparison. As is expected of alluvial soil sites, there is expected variation in the subsurface conditions. There are uncertainties in the hydraulic calculations and in the hydrologic data. Uncertainties also arise from the method used in estimating the applied bed shear stress in the EFA test and from the subjective decision that has to be made to operate the apparatus. A meaningful comparison between the measured and predicted scour depths will require these uncertainties and their effect on the predicted scour depths be quantified.

SURVEY OF STATE DOTS

The questionnaire and a summary of the survey can be found in Appendix B. All states interviewed for the questionnaire have an active scour monitoring program. For the most part, monitoring consisted of biannual bridge inspections consisting of visual observations. All interviewed states reported channel migration and abutment erosion to some degree for a few bridges. All states interviewed have not used the SRICOS method as the primary design method to predict scour in fine grained soils. The HEC-18 approach with varying degrees of empirical corrections to match observed conditions is currently employed by all states. Several states used an empirical reduction factor applied to the HEC-18 method to predict more realistic estimates of scour in cohesive soils. Several states applied experience, field observations, and engineering judgment to the HEC-18 results.

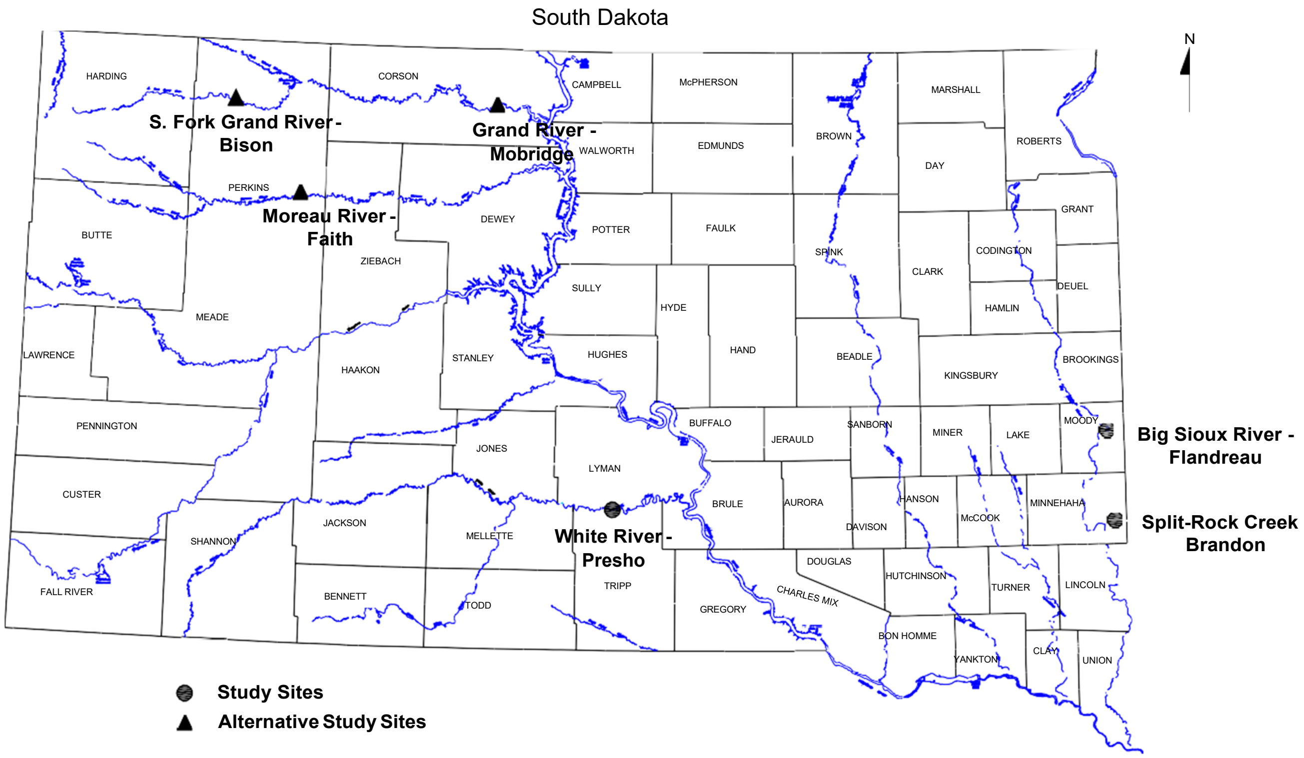
Research is currently active in studying and refining the SRICOS method. The Texas DOT is the most active in the area with several current, ongoing research projects. With the exception of the Texas DOT, soil erodibility measurements were limited to research projects. The listed advantages of the method were that it was designed to predict scour in cohesive soils, was designed to handle layered soils, and predicted time rate of scour for time history of flow. They listed the EFA testing as the primary disadvantage (cost, needing an erosion rate curve for soil strata change, and test accuracy).

BRIDGE SITE SELECTION

Three bridge sites in South Dakota were selected to evaluate the SRICOS method. They were the Big Sioux River Bridge near Flandreau on SD Highway No. 13, the Split Rock Creek Bridges near Brandon on Interstate 90 eastbound and westbound, and the White River Bridge near Presho on US Highway No. 183. A number of factors had entered into the final decision for selecting these sites. The primary objective of the project was to evaluate the SRICOS method. Therefore, the bridge sites selected should ideally satisfy the following requirements: (1) the predominant soil type is silt or clay; (2) scour profiles were measured on at least two dates separated by one or more major flood events; (3) these profiles show at least several feet of scour; (4) streamflow data exist at the site or can be reliably estimated; and (5) there is access to the bridge for a truck mounted drill rig. Other factors that were also considered include pier types, flow alignments and drainage areas. In addition, surveyed channel cross sections in the vicinity of the bridge crossings must be available in order to model the bridge hydraulics.

To evaluate the SRICOS method the current project relied heavily on archival data provided by the South Dakota bridge-scour project (1991-1995). This project was a cooperative effort between SDDOT and the South Dakota District of USGS. The final report of the project was published in Niehus (1996). In the South Dakota bridge-scour project, preliminary scour assessments were completed on 32 bridge sites in South Dakota, and detailed assessments were conducted on 12 out of those 32 sites. The detailed assessments were conducted for the period 1991-1993 and included hydrologic and hydraulic calculations, bed material analyses, scour measurements, streamflow measurements, and comparison of measured scour depths with predictions obtained using 16 published equations for pier, contraction and abutment scour. Based on this report, we determined that six of the 12 sites investigated in the detailed assessments (Grand River near Mobridge, Big Sioux River near Flandreau, Moreau River near Faith, South Fork Grand River near Bison, Split Rock Creek near Brandon, and White River near Presho) met the majority of our project requirements. The locations of these six bridge sites are shown in Figure 1. The individual reports for these six sites were obtained from the USGS for detailed study. Other information obtained from the USGS and SDDOT included surveyed channel cross sections, streamflow data, bridge inspection reports, field notes, bridge plans, and borehole data. The research team also visited the six bridge sites during spring and summer of 2007. The purposes of the field trips were to become familiar with the sites and to depict site conditions (e.g., apparent flow directions and concentrations, geomorphic characteristics, access to drilling) that might be useful to the project. A general description of the six bridge sites visited is given in Appendix C.

Table 1 summarizes the pertinent data for the six bridge sites visited. Of these six sites, only the Big Sioux River and White River Bridges met all our requirements. The four remaining sites all had less than 3 ft of measured scour. In addition, continuous streamflow record was not available at the Split Rock Creek site during 1991-1993. However, several methods exist for constructing synthetic hydrographs for un-gauged watersheds. Since it was one of the objectives of this project to provide guidance on how to apply the SRICOS method to un-gauged streams, the Split Rock Creek site was selected as one of the study sites. Together, the three bridge sites selected covered a wide range of stream types (small and large), drainage areas, flow alignments and pier types. Some of the unique characteristics of the study sites include long piers with large flow angle of attack (Big Sioux River Bridge), skewed bridges (Split Rock Creek Bridges), and river crossing at a sharp bend (White River Bridge). Because of the extensive flow data collected by the USGS at these sites in 1991 to1993, it was possible to compare the computed water surface elevations and flow velocities with field measurements to examine how well HEC-RAS modeled the bridge hydraulics at these sites.



Source: Figure prepared by South Dakota Department of Transportation in cooperation with the U.S. Department of Transportation Federal Highway Administration

Figure 10. Locations of bridge sites

Table 1. Summary of bridge site data (from Niehus, 1996) for 1991-1993.

	Grand River	Big Sioux River	Moreau River	South Fork Grand River	Split Rock Creek	White River
Drainage Area (mi^2)	5,470	4,096	2,660	1,350	446	9,343
Predicted 2-, 100- and 500-Year Discharges (ft^3/s)	5,370 36,100 53,300	2,320 31,300 53,100	3,870 36,900 58,200	1,440 17,300 32,700	2,200 22,500 39,200	9,860 48,000 71,800
Number of Surveyed Cross Sections	4	4	6	6	7	5
Date of Scour Measurements (Upstream) And Measured Discharge (ft^3/s)	8/26/91 (low flow) 3/9/93 (3,950)	6/20/92 (1,624) 6/22/92 (4,346) 3/30/93 (9,090) 7/7/93 (7,774)	8/27/91 (low flow) 6/11/93 (1,800) 7/21/93 (4,130) 7/27/93 (5,100)	6/17/92 (low flow) 3/10/93 (747)	7/2/92 (1,420) 3/29/93 (4,600) 5/8/93 (14,700)	8/22/91 (low flow) 5/8/93 (7,040)
Scour Measurements (Downstream)	No	12/5/91 6/22/92 3/30/93 7/7/93	6/16/92 6/11/93 7/21/93	No	12/6/91 3/29/93 5/8/93	4/16/92 5/8/93
Maximum Pier Scour Depth Measured (ft)	2	8.5	1-2	2-3	2-3	5
Maximum Contraction Scour Depth Measured (ft)	0	1	1-2	0	1	0
Flow Record And Maximum Daily Mean Discharge (ft^3/s)	Yes 3/7/93 (7,165)	Yes 7/5/93 (11,583)	Yes 7/28/93 (4,490)	Yes 3/8/93 (1,100)	Crest-Stage Partial Record 5/8/93 (18,900)	Yes 3/21/93 (10,000)
Soil Type	Sand and Silt	Silt and Clay	Sand and Silt	Silt and Clay	Silt and Clay	Sand and Silt
Access to Drilling	Abutment Only	Abutment Only	Abutment Only	Abutment Only	Abutment Only	Abutment and South Bank
Selected for Study	No	Yes	No	No	Yes	Yes

GEOTECHNICAL DATA

Geotechnical data collected for this project consisted of site reconnaissance at each of the study sites, hollow-stem auger borings, soil sample collection using a split spoon sampler and thin wall tubes, and geotechnical laboratory testing. Two borings were drilled at the Flandreau River Site, four at the Split Rock Creek site, and four at the White River site. Explorations were advanced to delineate subsurface conditions at each of the sites and were advanced to obtain thin wall tube samples for specific EFA testing. The geotechnical data are presented in Appendix D.

Generalized subsurface conditions at the Flandreau included about 15 feet of loose to medium dense fill soils overlying alluvial soils consisting of interbedded silts, clays and sands. At a depth of about 20 feet, black organic silt was encountered at the south abutment. Coarser grained materials were observed at the north abutment. Groundwater was observed at a depth of about 18 feet and 33 feet at the north and south abutments, respectively.

Generalized subsurface conditions at the Split Rock Creek site included about 10 to 15 feet of loose to medium dense fill soils overlying alluvial soils consisting of interbedded silts, clays and sands. More silts and clays were generally encountered at the east abutment with coarser grained materials being observed at the west abutment. Groundwater was observed at a depth of about 15 feet at the west abutment.

Generalized subsurface conditions at the White River site included about 9 feet of loose to medium dense fill soils overlying alluvial soils consisting of interbedded silts, sands, and gravels. Silts were generally encountered at the north abutment with coarser grained materials being observed at the south abutment. Groundwater was observed at a depth of about 26 feet at the north abutment.

SOIL EROSION RATE MEASUREMENTS

An erosion function apparatus (EFA) manufactured by Humboldt Mfg. Co. was used to measure the rate of soil erosion as a function of the applied bed shear stress. A detailed discussion of the EFA can be found in Briaud et al. (2001a). The apparatus consists of a rectangular water tunnel, 101.6 mm wide, 50.8 mm high and 1.25 m long mounted on a hydraulic bench. A pump draws water from a tank underneath the bench. The flow rate is regulated using a valve, and measured by a flow meter. The range of flow velocity that can be reached is between 0.1 and 6.0 m/s. In the EFA test, a thin wall tube sample is mounted perpendicular to the flow such that the open end of the tube is flush with the floor of the water tunnel. An electric motor and piston push the soil out of the tube 1 mm into the flow. The amount of time it takes to erode the 1 mm protrusion is measured and used to determine the erosion rate. The applied bed shear stress τ is calculated as $1/8\rho f V^2$, where f is the friction factor, ρ is the fluid density and V is the flow velocity (discharge/cross-sectional area) in the water tunnel. The friction factor is obtained either from the Blasius formula (for smooth bed) or the Colebrook formula (for rough bed). When the 1 mm of soil is eroded, the flow velocity is increased and the soil is again pushed 1 mm into the flow. This process is repeated a number of times with different flow velocities to establish the erosion rate versus shear stress curve. When the erosion rate is high, the soil is pushed 1 mm into the flow one at a time for a number of times and the erosion rate is calculated as the total amount of soil pushed divided by the total elapsed time. Figures 2 to 4 show several pictures of the EFA at the Minnesota Department of Transportation Materials Laboratory, which SDSU researchers had used to conduct the EFA tests.

The Blasius formula is valid for turbulent flow in smooth pipes ($\varepsilon = 0$). The Colebrook formula is used when the pipe roughness ε is not equal to zero. These equations are given by (e.g., Munson et al., 2006):

$$f = 0.316\mathrm{Re}^{-0.25} \qquad \text{(Blasius formula)} \qquad (1)$$

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \quad \text{(Colebrook formula)} \quad (2)$$

where $Re=VD/v$ is the Reynolds number, V is the cross-sectional average velocity, D is the equivalent pipe diameter, and v is the kinematic viscosity of water.

In the ideal situation when the soil erodes uniformly, the relevant roughness should be that of a smooth pipe (i.e., ε=0), since the structure of the wall boundary layer is established before the flow reaches the test section. When the soil surface is eroding non-uniformly, vortices and eddies are formed in and around the scour holes so the erosive action of the flowing water could be quite different from that in a simple shear flow. Currently, there is no consensus on how the bed shear stress should be calculated in this situation. At Texas A&M University, for example, the operator assesses the surface texture of the soil sample and estimates the bed roughness as the soil erodes. This estimation is performed on all the flow velocities tested. The process is inherently subjective, as it is unlikely that two different operators conducting separate EFA tests on duplicate soil samples would produce the same erosion rate curve. To give an example, Table 2 shows the EFA test results for boring B-1 P-7 from the Big Sioux River Bridge site. The table shows the bed shear stress calculated using four different values of ε (0, 1, 2 and 3 mm). As seen, the calculated bed shear stress varies significantly with the roughness height. Hence, the shape of the erosion rate curve can change considerably depending on the ε values assumed for the flow velocities tested.

Several problems were encountered in EFA testing. The flow velocity recorded by the EFA had to be corrected (see Appendix E). In addition, the stepping motor that operated the piston was underpowered. Thus, we had to use an extruder to get rid of some soils from the Shelby tube before the remaining soils could be advanced by the piston. This resulted in less soil available for EFA testing. During the test, the soil surface often eroded non-uniformly so it was difficult to determine when the sample should be advanced from the Shelby tube. It was also unsure what roughness height should be used to calculate the applied bed shear stress. For simplicity, a constant ε value was estimated by assessing the texture of the eroding surface. This roughness height was applied to all the flow velocity tested. The applied shear stress was also calculated for other ε values. An example is shown in Figure 5 for boring B-1 P-7 from the Big Sioux River Bridge. These additional erosion rate curves were used to conduct a sensitivity analysis to assess the effects of the critical shear stress and slope of the erosion rate curve on the predicted scour depths.

In all, twelve EFA tests were conducted at MNDOT by SDSU researchers. These included three thin wall tube samples from the Big Sioux River Bridge (B-1 P-7, B-2 P-12 and B-2 P-14), five samples from the Split Rock Creek Bridges (B-4 P-2, B-5 P-10, B-5 P-12, B-6 P-6 and B-6 P-8), and four samples from the White River Bridge (B-7 P-10, B-7 P-12, B-10 P-5 and B-10 P-7). Two additional thin wall tube soil samples (B-9 P-1 and B-9 P-2) from duplicate soil locations at the White River Bridge were tested by TAMU to assess the repeatability of the EFA tests conducted by SDSU. Duplicate samples were obtained by drilling an adjacent drill hole approximately 5 lateral feet from drill hole B-7 and obtaining soil samples at the same elevation as the adjacent samples (B-7 P-10 and B-7 P-12). All the samples were taken from drill holes in the left or right abutments. Boring logs, bridge plans, and channel profile measurements were studied to select the most probable representative samples at the bridge piers. The results of EFA tests are summarized in Appendix E. Of the 14 samples tested, the results from eight tests (B-1 P-7, B-2 P-12, Big Sioux River site; B-4 P-2, B-5 P-10, Split Rock Creek site; and B-9 P-1, B-9 P-2, B-10 P-5, P-10 P-7, White River site) were used with the SRICOS method to predict the local scour depths at a total of five different bridge piers from the three study sites.

Figure 11. Minnesota Department of Transportation erosion function apparatus.

Figure 12. Water tunnel and observation window. A thin wall tube is mounted perpendicular to the water tunnel.

Figure 13. Stepping motor and piston assembly. A thin wall tube is mounted perpendicular to the water tunnel.

Table 2. EFA test results for Big Sioux River Bridge; boring B-1 P-7, depth 19.5 to 21.5 ft, test 2. The soil is very silty fine sand.

V (m/s)	Re	τ (N/m^2) (ε =0 mm)	τ (N/m^2) (ε =1 mm)	τ (N/m^2) (ε =2 mm)	τ (N/m^2) (ε =3 mm)	Δz (mm)	Δt (s)	Δz/Δt (mm/hr)
1.703	115343	6.21	15.84	20.62	24.53	0	1124	0.0
1.905	129024	7.55	19.81	25.79	30.68	0	1124	0.0
2.044	138438	8.54	22.79	29.68	35.31	11	1124	35.2
2.265	153406	10.22	27.96	36.43	43.35	11	500	79.2
2.565	173725	12.71	35.83	46.70	55.58	11	284	139.4
2.702	183004	13.92	39.75	51.81	61.67	10	254	141.7

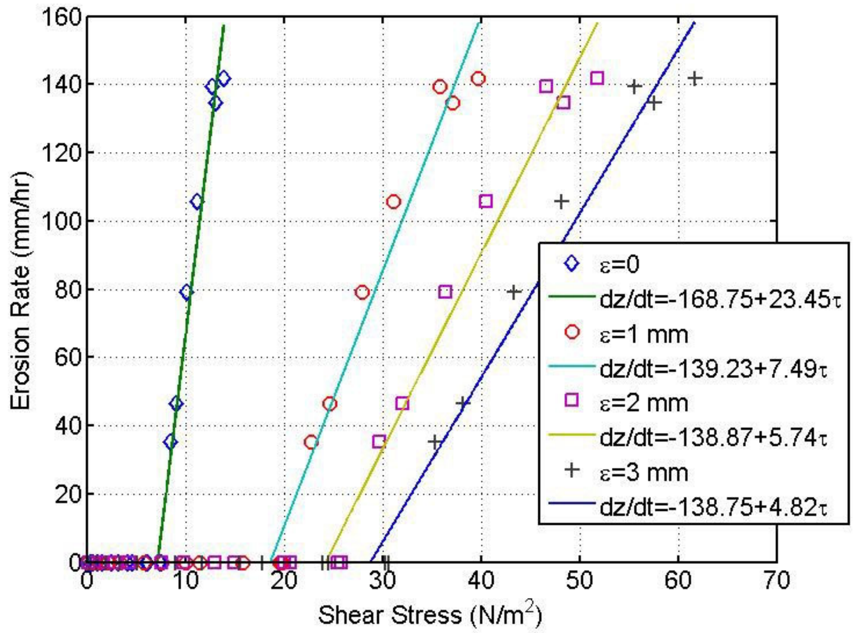


Figure 14. Erosion rate versus shear stress curve for Big Sioux River Bridge; boring B-1 P-7, depth 19.5 to 21.5 ft, tests 1 and 2, very silty fine sand.

BIG SIOUX RIVER BRIDGE

The SRICOS method was employed to predict local scour at the northern-most pier (bent 2) and southern-most pier (bent 4) for the period from June 22, 1992 to July 7, 1993. The general site soil conditions at bent 2 were very silty fine sand. When tested in the EFA, this soil eroded quickly particle by particle. The general site soil conditions at bent 4 were organic silt. This soil eroded slowly particle by particle and in chunks. The predicted final scour depth at bent 2 was 9.17 ft for the daily mean flow and 9.54 ft for the hourly mean flow. The entire predicted scour was produced by two large floods in June and July, 1993. These results compared favorably with the channel cross sections measured at different times and with the measured final scour depth of 8.5 ft measured at bent 2 on July 7, 1993. The SRICOS method predicted no scour at bent 4, which was also in agreement with field measurements.

Due to meandering of the river upstream of the bridge site, the flow velocity was much higher on the north side of the river crossing. The flow approached the northern-most pier with a large flow angle of attack (25 to 30 degrees during high flows, higher at moderate to low flows). The computed water surface elevations at the bridge agreed well with the field measurements, but HEC-RAS under-predicted the approach flow velocity at the northern-most pier by almost a factor of two. In the SRICOS simulation, the computed approach flow velocity at bent 2 was multiplied by a factor of 1.8 to match the measured velocity obtained by stream gauging. The uncertainties in approach flow velocity and flow angle of attack produced large uncertainty in the predicted final scour depth. Among the two, the approach flow velocity was the more critical parameter. It was found that varying the multiplying factor of 1.8 for the approach flow velocity by ±10% would change the predicted final scour depth by about 25% for increasing velocity and 35% for decreasing velocity.

Uncertainties in the critical shear stress and slope of erosion rate versus shear stress curve also produced large uncertainty in the predicted final scour depth. Between the two, the critical shear stress was the more critical parameter. The bed roughness height in the EFA tests could not be reliably estimated by assessing the surface texture of the soil sample. It was found that small variations in bed roughness height could produce large variations in the calculated bed shear stress. This affected the slope of the erosion rate versus shear stress curve as well as the critical shear stress.

Detailed results of the hydraulic and scour analysis for the Big Sioux River Bridge are presented in Appendix F. Using reasonable values for the input parameters, the SRICOS method produced computed scour that was comparable to the observed scour. However, the computed scour depth was very sensitive to the flow angle of attack, approach flow velocity, critical shear stress and slope of the erosion rate versus shear stress curves. It was concluded that application of the SRICOS method to flow conditions similar to those found at the Big Sioux River Bridge would require more accurate flow velocity calculations than those currently provided by one-dimensional river models. In addition, the accuracy of the EFA tests will also need to be improved.

SPLIT ROCK CREEK BRIDGES

SRICOS simulations were conducted to predict the local scour at bent 3 in the main channel of the westbound bridge. About 2 ft of local scour was measured between July 2, 1992 and May 8, 1993. Most of the scouring was believed to be produced by a major flood on May 8, 1993. Using the measured erosion rate versus shear stress curve for clay from the left abutment, the SRICOS method predicted that the local scour produced by the May 8 flood would be 1.43 ft, which is in qualitative agreement with field measurements. A continuous recorded hydrograph was not available for this site in 1992-1993. Two methods were used to estimate the flood history. In the first method, the measured hydrograph from Skunk Creek in a nearby watershed was scaled so that the peak discharge was the same as the recorded peak discharge at the Split Rock Creek sites. In the second method, a synthetic hydrograph was constructed using the Soil Conservation Service (SCS) dimensionless unit hydrograph. It was found that the predicted final scour depth is sensitive to the shape of the hydrograph, and specifically to the time to peak discharge.

This study also confirms that soil types can vary considerably (e.g., from cohesive to non-cohesive soils) from one side of the channel to the other, and drilling at the abutment cannot always provide reliable information on the soil stratigraphy at the bridge pier of interest. Our analysis shows that if the erosion rate versus shear stress curve for the sand from the right abutment was used in the SRICOS simulation, the predicted final scour depth at bent 3 would be 6.67 ft. In addition, there was large uncertainty in the calculated bed shear stress in the EFA test. The applied bed shear stress cannot be determined accurately by estimating the bed roughness. For cohesive soils, the bed roughness is very small but the threshold velocity for initiation of erosion can be very large. Since the bed shear stress is proportional to the flow velocity squared, a small increase in roughness height could produce a large increase in the calculated bed shear stress, leading to large uncertainty in the critical shear stress and the slope of the erosion rate versus shear stress curve. More reliable methods for determining the bed shear stress which do not require estimation of the bed roughness height are needed, especially for fine-grained soils. Furthermore, it is important to obtain geotechnical data (specifically, obtain thin wall tube samples) at each pier location.

The main advantage of the EFA is that soil samples from specific depths at the bridge site can be obtained with a thin wall tube and tested in the EFA relatively "undisturbed". However, this advantage is achieved at the expense of other drawbacks. First, the eroding surface (3 inches in diameter) in the EFA test is too small for accurate erosion rate measurements; soil heterogeneity and edge effects could have a significant effect on the measured soil erosion rates. Second, the erosive action of the water on the eroding surface cannot be determined reliably by estimating the bed roughness. The soil surface often erodes non-uniformly which may be the results of edge effects as well as soil heterogeneity. Once non-uniform erosion starts, there is no objective way to determine either the soil erosion rate or the applied bed shear stress.

The approach flow velocity is another important source of uncertainty in scour prediction using the SRICOS method. It was found that the approach flow velocity had a significant effect on the predicted final scour depth. However, at both the Big Sioux River and Split Rock Creek sites, the one-dimensional river model HEC-RAS had underestimated the approach flow velocity. It was shown that good agreement in the computed and measured water surface elevations could not ensure that the computed flow velocities were correct. Therefore, we need a better understanding of two-dimensional flow effects at bridge crossings and more accurate numerical results on bridge hydraulics for scour predictions.

WHITE RIVER BRIDGE

SRICOS simulations were conducted to predict the local scour at bent 2 and bent 3 in the main channel. Channel cross section measurements showed that about 5 ft of pier scour had occurred at bent 2 and 4 ft at bent 3 between August 22, 1991 and May 8, 1993. Using the measured erosion rate versus shear stress curves from the left and right abutments, the SRICOS method predicted local scour depths at the two main channel piers that were comparable to the measured scour. Fine-grained soils were found in the left abutment while coarser materials were found in the right abutment.

Our analysis showed that uncertainties in the EFA test results and computed flow velocities were again the two major sources of uncertainties in scour prediction using the SRICOS method. For soils that are very erodible, such as those found in the right abutment, the predicted final scour depth is insensitive to the critical shear stress and the slope of the erosion rate versus shear stress curve, and is determined mainly by the equilibrium scour depth of the largest flood in the hydrograph. In this situation, the pier scour depth predicted using the SRICOS method should be comparable to that predicted by the HEC-18 equation. For soils that are very erosion resistant, such as those found in the left abutment, both critical shear stress and slope of the erosion rate versus shear stress curve can have large effects on the predicted final scour depth. Between the two, the critical shear stress is the dominant parameter. As this case study has shown, adjusting the slope of the erosion rate versus shear stress curve alone may not produce the observed scour if the critical shear stress is outside a certain range. However, one can usually arrive at the observed scour by adjusting the critical shear stress and then the slope of the erosion rate curve.

The important flow parameters include flow depth and approach flow velocity. By itself, flow depth is only of secondary importance because the largest scour is caused by the large floods which generally produce large water depths, and laboratory experiments have shown that water depth effects are not important when the water-depth-to-pier-diameter ratio exceeds about 2.0. However, changing the water depth would change the approach flow velocity for a given discharge, and the approach flow velocity affects both bed shear stress and equilibrium scour depth. Thus, by adjusting the calculated approach flow velocity to match the measured velocity, we were able to re-produce the observed scour at bent 3 in the SRICOS simulation.

In HEC-RAS, calculated flow depth and flow velocity are dependent on the geometric data and the boundary conditions at the outflow boundary (for sub-critical flows). The effects of these inputs on the outputs are relatively well understood. For example, increasing the Manning n value would increase the water depth and decrease the flow velocity in the channel. For the White River Bridge, this effect was found to be very significant. Overestimating the reach length between the bridge and the downstream cross section (thus effectively reducing the channel slope) would also increase the computed flow depth at the bridge. The latter situation can arise when flow straightens at high flow but the effect is not included directly in the HEC-RAS computations. When the water depth downstream is unknown, it is a common practice to assume uniform depth at the outflow boundary. This is a reasonable approximation provided that the reach length between the bridge and the downstream cross section is sufficiently large so that the water surface elevation specified downstream does not have a significant effect on the water level at the bridge. This was found to be the case for the White River Bridge.

Flow discharge also affects the calculated scour depth. Hourly flow data were not available for the White River site, but SRICOS simulations at the Flandreau site has shown that hourly mean discharge would produce larger scour than daily mean discharge. This is logical because maintaining the same discharge for a longer period of time would not produce more scour once the equilibrium scour for that discharge has been reached. Whereas, increasing the discharge would increase the equilibrium scour depth and thus produce more scour. This will certainly be true if the erosion rates are sufficiently high that scour depths approach the maximum potential scour depths for the large floods. It should also be true for less erodible soils because the rate of scour decreases with time at a constant velocity, whereas the equilibrium scour depth increase as $Re^{0.635}$ (Re = pier Reynolds number). In other words, scour depth would increase faster by increasing the flow velocity than by increasing the flow duration. This also agrees with field observations that the large floods typically produce most of the observed scour.

We were able to produce predicted scour that was comparable to the observed scour by choosing the values of the input parameters within reasonable limits. However, the predicted scour depth was very sensitive to the soil erosion parameters and the approach flow velocities at the bridge. Hence, improving the accuracy of soil erosion rate measurements and computed flow velocities would be critical for implementation of the SRICOS method.

PARAMETRIC STUDY

Non site-specific sensitivity analyses were conducted to assess the effect of changes in individual input parameters on SRICOS model predictions for scour magnitude. This was accomplished by varying one parameter at a time and recording the associated changes in the SRICOS model response. The results of the scour computations show the SRICOS model is most sensitive to the critical shear stress. The results also show the SRICOS model is significantly sensitive to the flow angle of attack, and erosion function slope and somewhat sensitive to pier length and width/diameter. The SRICOS model appears to be not sensitive to upstream channel width, pier spacing, or number of piers. The effects of flow depth and approach flow velocity were not considered in this analysis. The non site-specific analysis focused on model sensitivity and was not site-specific.

USING THE SRICOS METHOD FOR SCOUR PREDICTION IN SMALL WATERSHEDS AND UN-GAUGED STREAMS

One of the difficulties in implementing the SRICOS method is to construct a hydrograph that would represent the hydrologic conditions most likely to be found at the bridge during its design life. A number of methods are available for constructing future hydrographs from estimated streamflow statistics. However, most of these methods are not easy to use. Furthermore, it is extremely difficult if not impossible to predict the hydrologic and hydraulic conditions at a bridge site reliably over many years. Therefore, the uncertainties in these predictions are not known. On the other hand, a multitude of methods have been developed for rainfall-runoff analysis for single floods. These methods are routinely used for flood control and floodplain studies, and have been extensively tested with field data so that their limitations are better understood. Using the recorded hydrographs for the Big Sioux River and Split Rock Creek Bridges, we found that a few large floods typically produced most of the predicted scour. Therefore, it is reasonable to design bridges to withstand scour produced by only a few large flooding events. The number of flooding events the bridge is to be designed for will depend on the recurrence intervals of the floods and the frequency of bridge inspections. A method is proposed wherein the SRICOS method is used with a sequence of design floods to predict scour. The method only requires information that is commonly available or can be easily estimated, such as peak flow, accumulated rainfall depth, drainage area and land cover. An example is presented in Appendix J by using a rectangular and a triangular hydrograph, but more sophisticated hydrographs can also be used if the required watershed parameters can be reliably estimated. The new approach is particularly well suited for bridges with low traffic volume roads, and for sites where flood durations are short and scouring events infrequent. As a final precaution, bridge inspection should be performed periodically and after the occurrence of major floods to ensure that the structure is safe.

IMPLEMENTATION RECOMMENDATIONS

The SRICOS method has been proposed to be the alternative design methodology for predicting scour at bridge piers in cohesive soils (HEC-18, 2001). Comparison of predicted and measured scour depths for three bridge sites in South Dakota indicates that the method can predict bridge pier scour depth within reasonable limits. The advantage of using the SRICOS method is, for highly scour resistant soils, the predicted final scour depth will be substantially less than the maximum equilibrium scour depth predicted by current methods. Therefore, footing and pile depths at bridge pier sites will not need to be as deep as is currently designed. This would result in substantial saving in bridge pier construction. The implementation recommendations presented below outline the tasks that will need to be accomplished by SDDOT over the next two to five years in order to successfully implement the SRICOS method.

1. USE THE SRICOS METHOD INITIALLY AS A SUPPORTING TOOL IN DESIGN OF BRIDGE FOUNDATIONS

In HEC-18 (2001), the SRICOS method is recommended as an alternative method for predicting scour at bridges founded on highly scour resistant cohesive soils where the useful life of the bridge is short in relation to the number of scouring floods and rate of scour, and bridges on low traffic volume roads that are monitored. HEC-18 cautions that the maximum or equilibrium scour depth should be used for bridges that have a long or un-determined design life. Also, the SRICOS method is not recommended for bridges that have a very large traffic volume, are not monitored, or serve hospitals or schools. These recommendations underlie concerns with the reliability of the method and our still limited understanding of the scouring process in cohesive soils and of the hydraulics and hydrology of bridge waterways. Furthermore, the SRICOS method requires a higher level of expertise in relation to subsurface exploration, laboratory testing, and hydraulic and hydrologic analysis in order to ensure reliable results. All of these require training and experience that will take time to develop. On the other hand, the SRICOS method represents a significant advance over existing methods. As improvements are made, the method may become more reliable and an accepted standard for design. SDDOT should be prepared to take advantage of these improvements and the substantial potential saving that the method could produce for the state.

Perhaps the best way to incorporate the SRICOS method in future design of bridge foundations is to introduce the method initially as a supporting tool. The predictions of the SRICOS method can be compared with predictions from existing methods to obtain more realistic estimates of scour depth in cohesive soils. This will eliminate the need to apply empirical reduction factor to the scour predictions obtained using current methods that were developed for non-cohesive soils. In applying the SRICOS method, it is recommended that the following procedures be followed:

- If a commercial EFA is used to measure soil erosion rates, the applied shear stress should be calculated assuming a smooth bed (i.e., bed roughness height = 0). This will under-estimate the critical shear stress and over-estimate the slope of the erosion rate versus shear stress curve. The predicted scour depth would then be on the safe side.

- Drilling and soil sampling for EFA testing should be conducted as close as practically possible to the bridge pier where the scour depth is to be predicted.

- The velocity distribution at the bridge site should be measured to determine the flow angle of attack and to depict any apparent flow concentration. The computed approach flow velocity can then be corrected if necessary. Ideally, these flow measurements should be conducted at high flows, but measurements at low and medium flows can still alert the design engineer to any potential problems with the hydraulic analysis.

- SRICOS method assumes that the equilibrium scour depth in cohesive soils is the same as in non-cohesive soils. Although recent research has indicated that the equilibrium scour depth in cohesive soils is less than that in non-cohesive soils, any empirical equations that relate the equilibrium scour depth to soil properties can be confidently applied only to the soils that were used to develop the equations. Hence, these equations may not be applied to the soils at the bridge site. Without a reliable test that tests soils from the bridge site to determine the equilibrium scour depth, it would be prudent to assume that the equilibrium scour depth in cohesive soils is the same as in cohesive soils. This implies that the equations in HEC-18 may also be used to estimate the equilibrium scour depth in the SRICOS method.

- Given the uncertainty of the SRICOS method at the present time and the complexity and difficulty in predicting the hydrologic conditions at a bridge site reliably over a long period of time, it is recommended that the SRICOS method should be applied to predict scour produced by only the large floods. Thus, the SRICOS method will be most useful for sites where flood scouring events are infrequent (e.g., ephemeral streams).

2. MONITOR CURRENT AND FUTURE RESEARCH TO OBSERVE IMPROVEMENTS TO THE SRICOS METHOD

The SRICOS method can be used to predict pier, contraction and abutment scour. However, the method has only been tested in the field for pier scour, and the variation of the predictions appears to be very high. The SRICOS method is an active area of research in bridge scour. It is recommended that SDDOT continues to monitor current and future research to observe new improvements to the method. Furthermore, SDDOT should become an active partner with other federal agencies and State DOTs to develop the SRICOS method. This may include supporting research to improve the method, training and continuing education of SDDOT personnel and its consultants to use the method as analysis and design tool, and acquiring the resources needed to implement the method.

3. CONDUCT WORKSHOPS TO TRAIN DESIGN ENGINEERS ON THE USE OF THE SRICOS METHOD

The SRICOS method is new to design engineers in South Dakota. It is recommended that SDDOT works with South Dakota State University to conduct some workshops to train SDDOT personnel and its consultants on the use of the method for scour evaluation. The workshops should cover different elements of the method, including subsurface exploration, laboratory testing, hydraulic and hydrologic analysis, and SRICOS simulation. These workshops will also provide an opportunity to increase awareness of bridge scour problems in the state and to inform design engineers of the technology and resources available for evaluation, analysis and design of bridge foundations to avoid scour related failure. It will be beneficial if the workshop participants can conduct an EFA test and use the test results to construct an erosion rate versus shear stress curve.

4. OBTAIN THE NECESSARY TESTING EQUIPMENT TO MEASURE SOIL ERODIBILITY

SDDOT will need an EFA in order to measure soil erodibility. An EFA will also be useful for assessing the potential of soil erosion in river channels and other hydraulic works. A commercial unit is currently manufactured by Humboldt Mfg. Co and had been purchased by a few universities and state highway laboratories in the United States. SDDOT can arrange to have its soil samples tested at these facilities. In the long run, it will be more economical to conduct its own soil erosion rate tests. Moreover, the applied shear stress cannot be determined accurately with the commercial unit. Georgia Institute of Technology had constructed their own EFA for measuring soil erosion rates. Their device utilized a tilting, re-circulating flume to erode the soil samples. The samples were advanced through the bottom of the flume into an open-channel flow using a piston and stepping motor in the same manner as the commercial EFA. However, the advantage of using an open-channel flume instead of a water tunnel is that the applied bed shear stress can then be calculated reliably from the measured hydraulic radius and slope of the hydraulic grade line. A rough bed can also be installed on the flume bottom to ensure fully developed turbulent flow, so that the erosive action of the flowing water is controlled by the boundary-layer turbulence generated upstream and not by the surface irregularities at the test section. It is recommended that SDDOT develops a similar device for use in South Dakota. SDDOT can work with SDSU to modify one of its existing flumes for EFA testing. The Fluid Mechanics Laboratory at SDSU has a 17 ft long, 0.67 ft high and 1.7 ft wide tilting flume. This flume can be tilted from 0 to 4% positive slope. The flume can be connected to an existing pumping system in the laboratory which has a maximum flow capacity of 8 ft^3/s. To give an example, a flow rate of 3 ft^3/s on a gravel bed (d_{50} = 4 mm) with a channel slope of 3% will produce a uniform water depth of 0.7 ft and a flow velocity of 6.4 ft/s. The corresponding bed shear stress will be about 20 N/m^2. Therefore, an open-channel flume is capable of producing bed shear stress at prototype scale. It is anticipated that a working EFA can be modified from an existing flume in six to twelve months.

5. ESTABLISH A PROCEDURE FOR COLLECTING SCOUR DATA IMMEDIATELY AFTER A MAJOR FLOOD

As the SRICOS method for predicting pier, abutment and contraction scour continues to evolve, there will be needs to verify the new improvements against additional field data measured at bridge sites. Ideally, flow and scour measurements should be taken at various times during a flood. It is recommended that SDDOT establishes a data collection plan to obtain these data. SDDOT can enlist the assistance of agency like the USGS to collect the field data during or immediately after a flood, and universities to analyze the data that have been collected. A range of bridge sites with high scour potential should be chosen to assess the performance of various components of the SRICOS method. Some of important parameters are bridge length, flow angle of attack, soil types, stream types (large and small), hydrologic conditions (continuous and transitory flows), abutment types, channel alignments, and flood-plain encroachments. A quick action response team should also be set up to assess scour damages of bridges after the occurrence of major floods. This present project had benefited tremendously from the archival data provided by the South Dakota bridge-scour project (1991 to 1995). A comprehensive database of collected field data in bridge scour and channel degradation should be maintained at SDDOT and/or the state universities for scour management and future research.

6. CONDUCT RESEARCH TO IMPROVE THE PREDICTIONS OF HYDRAULICS OF BRIDGE WATERWAYS AND TO UNDERSTAND THE EFFECT OF TEMPORAL STRUCTURE OF HYDROGRAPH AND SOIL TYPES ON TIME RATE OF SCOUR

Approach flow velocity has a significant effect on scour depth. The equilibrium scour depth is proportional to $V_1^{0.635}$ (Equation A-1) and the maximum initial bed shear stress is proportional to V_1^2 (Equation A-11). Underestimating the initial bed shear stress has the same effect as over-estimating the critical shear stress. Both will lead to under-estimation of scour depth. This present study has demonstrated that a one-dimensional river model such as HEC-RAS may not predict the velocity distribution at bridge crossings accurately in some situations. Currently, there is little information to guide the engineer in recognizing the conditions under which two-dimensional flow effects may be important. The need to predict two-dimensional flow effects at bridges becomes even more important when predicting contraction scour where the results may be very sensitive to how the width of the approach flow is defined. It is recommended that SDDOT initiates a research project to study two-dimensional (2-D) flow effects in bridge waterways. The project should include a detailed literature review on 2-D flow effects at bridges, identify the site characteristics that produce 2-D flow effects, compare the performance of 1-D and 2-D models in bridge hydraulics analysis, and develop procedures to guide the engineer in selecting the appropriate modeling techniques for bridge hydraulics analysis.

To use the SRICOS method for scour prediction, it is necessary to construct a flow discharge versus time curve or hydrograph at the bridge site. Presently, the effect of temporal structure of hydrograph and soil erodibility on scour depth is poorly understood. Because of this, it is unclear what level of detail is necessary in the hydrologic modeling in order to obtain reliable scour predictions. A logical first step to address this problem may be to examine the predicted scour histories produced by simulated and/or measured hydrographs. This analysis needs to be repeated for different soil types. Intuitively, it should be easier to predict scour depth produced by a few large floods reliably than over the design life of the bridge, especially for un-gauged streams where streamflow records are lacking. Evaluating bridges for scour based on a few large floods will also allow the engineer to take advantage of the multitude of techniques available for rainfall-runoff analysis. The important input parameters will include the magnitude and duration of the design floods, the number of floods, and the acceptable risk. A preliminary investigation was conducted in this project, but the basic approach needs further refinement to define its limitations and assumptions and the inherent risk in using this approach.

REFERENCES

Briaud, J.-L., Chen, H. C., Kwak, K. W., Han, S. W. and Ting, F. C. K. (2001b). “Multiflood and multilayer method for scour rate prediction at bridge piers.” *J. Geotechnical and Geoenvironmental Eng.*, ASCE, 127(2), 114-125.

Briaud, J.-L., Chen, H. C., Li, Y., Nurtjahyo, P. and Wang, J. (2004). “Pier and contraction scour in cohesive soils.” NCHRP Report 516, Transportation Research Board, Washington D. C.

Briaud, J.-L., Ting, F. C. K., Chen, H. C., Han, S. W. and Kwak, K. W. (2001a). “Erosion function apparatus for scour rate predictions.”*J. Geotechnical and Geoenvironmental Eng.*, ASCE, 127(2), 105-113.

Curry, J. E., Crim, Jr. S. H., Guven, O., Melville, J. G. and Santamaria, S. (2003). “Scour evaluations of two bridge sites in Alabama with cohesive soils.” Final report for Alabama Department of Transportation Research Project 930-490R.

Ghelardi, V. M. (2004). “Estimation of long term bridge pier scour in cohesive soils at Maryland bridges using EFA/SRICOS.” M.S. thesis, Department of Civil Engineering, University of Maryland, College Park, Maryland.

Munson, B. R., Young, D. F. and Okiishi, T. H. (2006). *Fundamentals of Fluid Mechanics*, John Wiley & Sons.

Niehus, C. A. (1996). “Scour assessments and sediment-transport simulation for selected bridge sites in South Dakota.” USGS Water-Resources Investigations Report 96-4075.

Richardson, E. V. and Davis, S. R. (2001). “Evaluating scour at bridges.” Report no. FHWA-NHI-01-001 (HEC-18), Federal Highway Administration, Washington, D. C.