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Design and Evaluation of Scour for Bridges Using HEC-18

(Volume 1 of 3)

FINAL REPORT
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16. **Abstract**

The overall objective of this research is the development of a new approach for evaluating bridge scour for New Jersey's bridges on non-tidal waterways. The study commenced with a web-based survey of scour practice within the U.S. and a literature review of predictive scour models. The major project deliverable is a new Scour Evaluation Model (SEM), which is a tiered, parametric, risk-based decision tool. A variety of geotechnical, hydrologic, and hydraulic data are analyzed to generate risk ratings for a particular bridge. These ratings are then inputted into a Risk Decision Matrix to generate a scour priority level and recommended actions, which may range from expedited installation of countermeasures to removal from scour critical status. Bridge importance is also factored into the final priority level. In addition, the New Jersey SEM provides standard protocols for: (1) erosion classification of sediments; (2) application of scour envelope curves; and (3) analysis of hydrologic data. The model was validated and calibrated by inspecting scour critical bridges and comparing actual field observations with model results. While the current model reflects New Jersey's geology and hydrology, it can be recalibrated to other regions or states. The model is principally designed to evaluate scour risk of existing bridges, but many model components are useful for designing new bridges as well. Included are example SEM applications for 12 bridges and two detailed example problems.

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Appendix C: Example Investigative Reports

SEM analyses require that three kinds of reports be generated for each bridge studied: (1) Geotechnical Reconnaissance Study; (2) Field Scour Investigation; and (3) Reconnaissance Hydrologic Analysis. These reports are not included in this document due to length restrictions. However, examples of each are available upon request from the Department of Civil and Environmental Engineering at the New Jersey Institute of Technology. Contact: Dr. John Schuring at schuring@njit.edu.

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LIST OF ACRONYMS

AASHTO – American Association of State Highway and Transportation
ACBs – Articulated Concrete Blocks
ADT – Average Daily Traffic
ARF – Average Risk Failure
ASTM – American Society for Testing and Materials
BIM – Bridge Importance Matrix
COF – Consequence of Failure
CSU – Colorado State University
DOT – Department of Transportation
DR – Detour Risk
EFA – Erosion Function Apparatus
FDOT – Florida Department of Transportation
FEMA – Federal Emergency Management Agency
FHWA – Federal Highway Administration
HEC-18 – Hydraulic Engineering Circular No. 18
ICSE-5 – 5th International Conference on Scour and Erosion
ILDOT – Illinois Department of Transportation
NBIS – National Bridge Inspection Standards
NBSD – National Bridge Scour Database
NCHRP – National Cooperative Highway Research Program
NJDEP – New Jersey Department of Environmental Protection
NJDOT – New Jersey Department of Transportation
NJIT – New Jersey Institute of Technology
NWS – National Weather Service
PennDOT – Pennsylvania Department of Transportation
POA – Plan of Action
RQD – Rock Quality Designation
SCDOT – South Carolina Department of Transportation
SDI – Slake Durability Index
SEM – Scour Evaluation Model
SHA – State Highway Administration
SI&A – Structure Inventory and Appraisal
SRICOS – Scour Rate in Cohesive Soils
SRICOS-EFA – Scour Rate in Cohesive Soil – Erosion Function Apparatus
TXDOT – Texas Department of Transportation
US – United States
USDA – United States Department of Agriculture
USDOT – United States Department of Transportation
USGS – United States Geologic Survey
USSCS – United States Soil Conservation Service
WMA – Water Management Areas

EXECUTIVE SUMMARY

Design and Evaluation of Bridges for Scour Using Hydraulic Engineering Circular No. 18 (HEC-18)

In an effort to improve scour design and evaluation methods within the State of New Jersey, the New Jersey Department of Transportation (NJDOT) engaged the New Jersey Institute of Technology (NJIT) to perform a bridge scour research study under Task Order No. 89. The NJIT research team was comprised of faculty, a consultant, and students within the Department of Civil and Environmental Engineering with diverse specialties including hydraulic engineering, hydrology, geotechnical engineering and bridge engineering, reflecting the multidisciplinary nature of the scour phenomenon. All research was done in consultation with the NJDOT Research Project Manager and the NJDOT Research Customer. In addition, a Scour Project Implementation Committee was formed consisting of members from several NJDOT divisions, as well as the offices of the Federal Highway Administration (FHWA) and the United States Geological Survey (USGS). The Implementation Committee convened periodically to review the research results and provide feedback.

The overall objective of this study was to develop a rational and defensible process for estimating scour depths for New Jersey's bridges on non-tidal waterways. The study commenced with a comprehensive literature review of theory and predictive models for bridge scour. This included a web-based survey of scour practice for DOTs within the U.S. in order to assess the varied scour design and evaluation methods used by transportation agencies. HEC-18 methods and other available models and best practices were critically reviewed and compared to develop the most appropriate scour evaluation procedure for New Jersey. The study also investigated the geotechnical, hydrologic, and hydraulic factors affecting scour behavior. In addition, a detailed review of the Stage II studies for the bridges on New Jersey’s Scour Critical List was undertaken to identify significant parameters and trends.

The major project deliverable is a new Scour Evaluation Model (SEM) that reflects New Jersey’s unique geologic and hydrologic/hydraulic conditions. In general, the New Jersey SEM is a tiered, parametric, risk-based decision tool. In applying the model, a variety of geotechnical, hydrologic, and hydraulic data are inputted for a particular bridge. These data are analyzed to determine two risk ratings, one geotechnical and the other hydrologic/hydraulic. The user then enters the risk ratings into a two-dimensional Risk Decision Matrix to generate a priority rating that varies according to risk level. This, in turn, generates recommended actions, which may include priority installation of countermeasures, real time scour monitoring, or removal from the Scour Critical List. Bridge importance (ADT and detour length) is also evaluated and factored into the final priority rating. A complete set of flowcharts are provided for application of the SEM. Although the model is principally designed to evaluate the scour risk of existing bridges, some of the model components are useful for designing new bridges as well.

The overall purpose of the New Jersey SEM is to improve bridge safety and allow the NJDOT to expend repair funds more strategically. The method, which is documented in this report, will allow the Department to discern more precisely those bridges which are scour critical and require protective measures. The SEM procedure is also capable of identifying other bridges that can be returned to a normal or modified monitoring program. While the current model reflects New Jersey's geology and hydrology, it can be recalibrated to other regions or states.

The SEM procedure also assures that scour evaluations for bridges are performed in a uniform manner. Standard protocols are provided for conducting geotechnical reconnaissance studies and field scour investigations to evaluate and document scour risk. Included is a new classification system that rates the erosion resistance of the streambed according to the kind of soil or rock present. Seven different erosion classes are defined ranging from sound rock to soft clay.

The SEM also provides standard methods for conducting hydrologic and hydraulic evaluation of scour risk. One method is envelope curve analysis, which defines the upper range of observed scour depths in a specific geologic region. This study recommends that envelope curves be applied to certain bridges in State's Coastal Plain and Non-glaciated Piedmont/Highlands provinces. The study also employs hydrologic/hydraulic analyses, which determine whether a bridge has experienced a 100-year storm. Several data sources were utilized including stream gages, StreamStats runs, and weighted USGS flows.

The majority of this research study was conducted when HEC-18, 4th edition was the prevailing guidance document. This edition contained very limited information for analyzing scour in some of the geologic conditions present in New Jersey, such as bedrock, boulder trains, and hard cohesive soils. With the publication of the 5th edition in 2012, new scour relationships became available and were reviewed and validated. SEM now incorporates those parts of HEC-18 appropriate for New Jersey geology and bridges.

During the final phase, the New Jersey Scour Evaluation Model was validated and calibrated by inspecting 34 bridges on the Scour Critical List. Bridges were selected in all four of the New Jersey's physiographic provinces to examine a range of geologic and hydrologic conditions. Actual field observations were compared and correlated with model results. The study report also presents example SEM applications for 12 selected scour critical bridges, determining preliminary risk and priority levels for each. In addition, two detailed example problems are provided to further instruct the user in the application of the SEM.

The New Jersey SEM will be applied to the remaining 142 bridges on the State's Scour Critical List for possible status change. Those bridges determined to have the highest scour priority will be placed on a list for expedited monitoring, repair, or replacement. Preliminary results also suggest that a significant number of bridges are candidates for removal from the Scour Critical List over the next few years, with the potential to save the Department tens of millions of dollars.

Planning is currently underway at NJDOT to launch an “Implementation Phase” to transfer the results of this research into state-wide practice as expeditiously as possible. The project will be divided into three principal tasks. The first will be to evaluate selected scour critical bridges using SEM to fully demonstrate the method. The key finding for each bridge will be the Priority Level generated by the model (1 thru 4) along with the Recommended Actions. The second task of the project will be to develop envelope curves for selected bridges in the Coastal Plain and Non-glaciated Piedmont/Highlands provinces of the New Jersey. These state-specific data will be added to the national database of envelope curves, adding yet another degree of confidence to the method. The third and final task of the Implementation Phase will be to present an instructional seminar in the use of New Jersey SEM to NJDOT personnel and design consultants.

INTRODUCTION

Background

Prevention of bridge scour has now been a national priority for 2 full decades. Beginning in 1990 with the Federal Highway Administration's (FHWA's) issuance of Technical Advisory T5140.20, transportation agencies across the U.S. have been deliberately engaged in evaluating the scour susceptibility of bridges within their inventories (USDOT, 1988). Those bridges found to be scour critical are now in various stages of remediation, ranging from monitoring to outright replacement. While progress is being made, many state and county DOTs are still in the process of implementing their action plans. The reason for the delay is the sheer number of bridges that detailed screening has determined to be scour susceptible, which number into the hundreds in some states.

Prudent action is warranted, since scour remains a leading cause of bridge failure in the U.S. Fortunately, the large majority of the failures are not sudden or catastrophic. More commonly, the responsible agency observes progressive erosion and scour, and then decides to repair the bridge or replace it preemptively.

For riverine flow the principal scour tool for U.S. bridge designers is Hydraulic Engineering Circular No. 18 (HEC-18) published by the FHWA (Arneson et al., 2012). Increasingly, practitioners recognize that some of the standard equations in HEC-18 over-predict scour depth for certain hydraulic and geologic conditions. One reason for overly conservative or erroneous calculated scour depths is poor estimation of scour variables. Misuse of methods can also be a culprit, such as applying a HEC-18 equation to a bed sediment or hydraulic condition that does not actually fall within the usable range of the relationship.

Another explanation for over-prediction of scour depth is that most of the HEC-18 relationships are based on laboratory flume studies conducted with sand-sized sediments increased with factors of safety. It is fair to ask whether scale modeling can effectively represent a phenomenon as complex as scour, especially in view of the wide diversity of hydrologic, hydraulic, and geotechnical conditions that exists across the nation. Indeed, the scour behavior of a bridge spanning a mile-wide river with silty sediments in the Midwest is quite different from a bridge crossing a boulder-filled stream in the Mountain States, which differs yet again from another bridge spanning a modest-size river choked with coarse glacial outwash in the Northeast. Recognizing such regional differences, and driven by the funding limitations, it is prudent to re-examine predictive scour models.

The impact of over-predicting scour depth for new bridges can be significant, since designers have only two general options: (1) extend and/or stiffen the substructure; or (2) provide countermeasures. Either option increases construction costs substantially. When retrofitting existing bridges for scour, additional complications may be encountered. One is the acquisition of right-of-way easements, since installed countermeasures typically extend beyond the bridge limits. A second is the environmental impact of the countermeasure on the flora and fauna present within the stream channel. Lengthy permit approval times can occur for bridges located along environmentally sensitive watercourses.

A principal motivation for this current research project was to develop a more discerning scour evaluation procedure to ensure that bridges on the scour critical list are actually critical. For example, the Research Team found that the majority of Stage II studies for the bridges on the scour critical list did not satisfactorily characterize the grain size of the stream bed materials on account of inadequate sampling methods. This caused a bias towards finer grain sizes in at least half of the bridges studied, which, in turn, inflated predicted scour depths. In addition, numerous inconsistencies were found in the hydraulic and hydrologic analyses. As an example, stream discharges were developed using many different methodologies (e.g. extreme value, regression analysis), as well as data from different agencies (e.g. FEMA, USSCS, USGS). These inadequacies in the Stage II studies had the effect of compounding, even further, the degree of conservatism already built in the HEC-18 relationships. Note that some instances of under-conservatism were also encountered in the Stage II studies, which were also of concern.

Project Objectives

In an effort to improve scour design and evaluation methods within the State of New Jersey, the New Jersey Department of Transportation (NJDOT) engaged the New Jersey Institute of Technology (NJIT) to perform the current research study under Task Order No. 89. The NJIT research team was comprised of faculty, a consultant and students within the Department of Civil and Environmental Engineering with diverse specialties including hydraulic engineering, hydrology, geotechnical engineering and bridge engineering, reflecting the multi-disciplinary nature of the scour phenomenon. All research was done in close consultation with the NJDOT Research Project Manager and the NJDOT Research Customer. In addition, a Scour Project Implementation Committee was formed consisting of members from several NJDOT divisions, as well as the offices of FHWA and USGS. The Implementation Committee convened periodically to review the research results and provide feedback.

The overall objective of this study was to develop a rational and defensible process for estimating scour depths for New Jersey's bridges on non-tidal waterways. The study commenced with a comprehensive literature review of theory and predictive models for bridge scour. This included a web-based survey of scour practice for DOTs within the U.S. in order to assess the varied scour design and evaluation methods used by transportation agencies. HEC-18 methods and other available models and best practices were critically reviewed and compared to develop the most appropriate scour evaluation procedure for New Jersey. The study also investigated the geotechnical, hydrologic, and hydraulic factors affecting scour behavior. In addition, a detailed review of the Stage II studies for the bridges on New Jersey's Scour Critical List was undertaken to identify significant parameters and trends.

The majority of this research study was conducted when HEC-18, 4th edition (Richardson and Davis 2001) was the prevailing guidance document. This edition contained very limited information for analyzing scour in some of the geologic conditions present in New Jersey, such as bedrock, boulder trains, and hard cohesive soils. The Research Team developed new methods for dealing with these special conditions. With subsequent publication of the 5th edition of HEC-18 in 2012, new guidance became available for a wider range of geotechnical conditions, and this document now incorporates selected HEC-18 methods appropriate for New Jersey geology and bridges.

The major project deliverable is a new Scour Evaluation Model (SEM) that reflects New Jersey's unique geological and hydrologic/hydraulic conditions. The method, which is documented in this report, will allow NJDOT to discern more precisely those bridges which are scour critical and require protective measures. The SEM procedure is also capable of identifying other bridges that can be returned to a normal or modified monitoring program. The model is risk-based and encompasses geotechnical, hydrologic, and hydraulic factors. It is planned to apply the New Jersey Scour Evaluation Model to the 140+ bridges remaining on the State's Scour Critical List for possible status change. The SEM is useful for the design of new bridges as well. While the current model reflects New Jersey's geology and hydrology, it can be recalibrated to other regions or states.

Scope and Techniques of the Research Study

Phase 1 - Literature Search

The Literature Search Phase was an important first step in the study, and it formed the essential foundation for later analyses and development of the new scour evaluation model. There is clearly a large body of knowledge on bridge scour, so the NJIT Research Team took a multipronged search approach by utilizing reference library and internet mining, as well as meetings with key agency offices, private companies, and individuals possessing relevant data. The search was conducted at two "hierarchical levels." First, a general scan of all available sources was made. The second level of the search involved a focused examination of selected sources with direct bearing on New Jersey's scour program.

A highlight of the Literature Search Phase was a web-based Scour Practice Survey conducted by the NJIT Research Team to assess current scour practice used by transportation agencies within the U.S. and Canada. The 10-question survey, conducted in summer July 2009, queried agencies about their scour design standards, experiences with failures, monitoring programs, and countermeasure preferences. Response to the Scour Practice Survey was notably strong with a response rate of better than 70 percent. A number of respondents forwarded failure data, as well as documentation of alternative methods for scour analysis that were valuable in the current study.

An Interim Literature Search Report was submitted to NJDOT and to the Scour Project Implementation Committee in October 2009.

See the following report sections for a summary of the Literature Search Phase results:

- Chapter, "SUMMARY OF NEW JERSEY'S SCOUR PROGRAM" on page 10.
- Chapter, "SURVEY OF SCOUR PRACTICE" on page 16.

In addition, a paper was presented and published about the Literature Search Phase results at the Fifth International Conference on Scour and Erosion (ICSE-5). The citing is as follows:
Schuring, John R., Robert Dresnack, Eugene Golub, M. Ali Khan, Matthew R. Young, Richard Dunne, and Nazhat Aboobaker, "Review of Bridge Scour Practice in the U.S.," *ASCE Geotechnical Special Publication No. 210, Scour and Erosion, Proceedings of the Fifth International Conference on Scour and Erosion*, Nov. 7-10, 2010, San Francisco, CA, pp. 1110-1119.

Phase 2 – Investigative Research Study

Tasks 1 & 2: Review, Classify and Validate Available Scour Models

As a starting point for modification of the Department's method of scour analysis, the Research Team examined the principal HEC-18 design relationships and their original reference sources. In addition, a number of comparative scour studies (calculated vs. predicted) were compiled and alternate analysis methods reviewed. With the publication of the 5th edition of HEC-18 in 2012, some new scour relationships were introduced. The most promising of the available scour methods are presented in this research report.

Owing to the complexity of the scour phenomenon, satisfactory analytical solutions range from difficult to impossible. Therefore, there is tremendous value in studying actual scour failures to better understand the physical mechanisms and causative factors. Thus, the Research Team undertook an extensive review of scour failures in the U.S. and abroad dating back more than 50 years.

See the following report sections for a summary of Tasks 1 & 2 results:

- Chapter, "REVIEW OF TRADITIONAL AND ALTERNATE METHODS FOR SCOUR ANALYSIS" on page 22.

Task 3: Apply Selected Models to Stage II Data

The Stage II studies for the State's original 165 scour critical bridges were obtained from the Department's archive located at the offices of AECOM in Bloomfield, New Jersey. These were reviewed, and a master database of key parameters related to scour behavior was compiled. These data were examined for significant trends and method consistency. During the Literature Search Phase, and again during the developmental stage of the new scour model, the Stage II data were run through various scour equations for comparative purposes. Stage II data also served as an important input component for the validation and calibration activities for the new model.

Stage II data is used throughout the report, but especially in:

- Report section, “Field Visits for Validation and Calibration of the Model” on page 79.

Task 4: Investigate Geotechnical and Hydrologic/Hydraulic Factors

The reviews of Task 3 showed certain inconsistencies in both the geotechnical and hydrologic/hydraulic analyses contained within the Stage II studies. For example, Stage II geotechnical investigations did not always satisfactorily characterize the grain size of the streambed materials. In a number of cases, the results were skewed towards a finer texture, leading to scour over-prediction at those bridge sites. In addition, there was considerable non-uniformity among the hydrologic approaches used to estimate the design flows for the Stage II studies. This resulted in both over- and under-prediction of scour for some bridges. It was concluded that the scour rating statuses of a number of bridges on the Scour Critical List are not representative of actual risk.

The Research Team used these findings to develop an improved and more realistic approach for evaluating scour risk. New detailed guidelines are presented in this report to investigate, document, and analyze geotechnical, hydrologic, and hydraulic factors related to scour. These are incorporated into the new scour evaluation model.

See the following report sections for a summary of Task 4 results:

- Chapter, “GEOTECHNICAL EVALUATION OF BRIDGE SCOUR” on page 29.
- Chapter, “GUIDELINES- HYDROLOGIC/ HYDRAULIC EVALUATION OF SCOUR RISK” on page 50.

Task 5: Develop Scour Design Guidelines

A new method for analyzing scour risk was developed as part of this study. The New Jersey Scour Evaluation Model (SEM) is designed to reflect the State’s unique geological and hydrologic/hydraulic conditions. The SEM method will help to discern those bridges which are scour critical and require protective measures. The SEM is also capable of identifying other bridges that can be returned to a normal or modified inspection monitoring program.

The SEM method was validated and calibrated using data from nationally published databases. In addition, the Research Team also made field visits to 34 scour critical bridges throughout the State to collect scour data for validation and calibration. Extensive use was also made of historical stream gaging data and the new USGS StreamStats software. SEM also incorporates selected HEC-18 scour analysis relationships that have shown reasonable correlation with field scour observations at New Jersey bridges.

See the following report sections for a summary of Task 5 results:

- Chapter, “NEW JERSEY SCOUR EVALUATION MODEL (SEM)” on page 61.
- Report section, “Field Visits for Validation and Calibration of the Model” on page 79.

Task 6: Reporting and Implementation

This entire report and its accompanying appendices constitute the reporting requirements for Task 6 of the current study. In addition, the first part of the Implementation Phase for SEM is presented in this report as example problems for selected scour critical bridges.

As of this writing, the Department is scheduled to launch a full Implementation Phase for TO-89 to transfer the results of this research into state-wide practice as expeditiously as possible. The scope will include: (1) Evaluation of selected scour critical bridges using SEM to fully demonstrate the method; (2) Development of envelope curves for selected bridges in the Coastal Plain and Non-glaciated Piedmont/Highlands provinces of New Jersey; and (3) Presentation of an instructional seminar about SEM to the Department and design consultants.

The first part of the Implementation Phase for this research is presented in the following chapter section:

- Report section, “Example Model Applications to Selected Scour Critical Bridges” on page 79.

SUMMARY OF NEW JERSEY'S SCOUR PROGRAM

During the research study, numerous scour program documents were reviewed, beginning with Stage I studies and extending all the way up to Plan of Action status reports. Exploratory meetings were also held with a number of Department offices, government agencies, private consultants, and other individuals possessing relevant knowledge of the State's scour program. This chapter presents a chronological summary and discusses the status of New Jersey's Scour Program, thus establishing the context for this research study.

Chronology of NJ's Scour Program

1990-1994: Stage I – Screening and Prioritization

In 1990, the New Jersey Department of Transportation (NJDOT) launched a statewide Scour Evaluation Program in response to catastrophic collapses of some bridges due to scour that occurred during the late 1980's within the U.S and abroad. The impetus for New Jersey's program was Technical Advisory T5140.20 issued by the Federal Highway Administration (FHWA). The focus of the program was the nearly 2,400 existing State and county highway bridges over waterways. TAMS Consultants Inc. was selected as the lead technical and management consultant to assist the Department in the development and implementation of the scour program. In addition, 16 other consultants were engaged to perform the engineering aspects of the scour screening and evaluation.

The Stage I evaluations involved the collection of readily available data and a field visit to each bridge site. The field visits were made by an interdisciplinary team of experienced hydraulic, structural, and in some cases, geotechnical engineers. Through the use of standard data forms and appraisal criteria, the potential susceptibility to scour damage was evaluated for each bridge. Among the key factors considered during the Stage I evaluations were foundation type, collapse vulnerability, waterway characteristics and history of scour problems. Based on these efforts, two numerical appraisal ratings were determined for each bridge including a Scour Sufficiency Rating (from 0 to 100) and a Prioritization Category Rating (from 1 to 4).

In April 1994, TAMS issued a Stage I summary report for the State-owned structures. A total of 313 State bridges were initially identified as scour susceptible and therefore became candidates for a Stage II in-depth evaluation. However, the number of scour susceptible bridges has changed through the years on account of ongoing reconstruction programs, changed scour conditions at some bridge sites, and results from in-depth scour evaluations.

1994-2005: Stage II – In-Depth Scour Evaluation

In 1994, Stage II In-Depth Scour Evaluations commenced and were carried out in four phases. Phases 1 and 2 dealt primarily with bridges with known foundation types and structures over non-tidal waterways. Phase 3 included scour susceptible bridges with unknown foundations and/or bridges over tidal waterways. Phase 4 dealt with the remaining bridges over tidal waterways or with unknown foundations, as well as some bridges with scour susceptible foundations that were experiencing scour related problems. Scour susceptible bridges scheduled for replacement under the Department's Capital Program within 5 years were removed from the Stage II evaluation list. The rationale was that the replacement structure would be designed to resist scour in accordance with HEC-18, thus eliminating the need for any further efforts. However, a monitoring program was implemented for these bridges until construction commenced.

In order to provide consistency among consultants in the evaluation and documentation of bridges studied during Stage II, the Department issued a 'Guidelines Manual' in June 1994. New Jersey's Stage II Program included the following tasks: (1) Data Collection and Review; (2) Field Investigation; (3) Determination of Scour Analysis Variables; (4) Scour Analysis and Evaluation; (5) Evaluation of Countermeasures; and (6) Bridge Scour Evaluation Report.

All Stage II evaluations followed the analysis procedures described in HEC-18, which included determination of the waterway characteristics for flood flow conditions, calculation of potential scour depths at the substructure units, and assessment of substructure stability. Those bridges whose foundations were judged to be unstable for the calculated scour depths were classified as "scour critical" and appropriate countermeasures were recommended. Scour depths at three storm events (50-, 100- and 500-year) were evaluated, and as per the current FHWA criteria, a finding of unstable footings at any of the storm events could lead to a scour critical classification.

Upon completion of the Stage II in-depth scour evaluations, a total of 165 bridges were determined to be "scour critical." Excluded from this final list were bridges currently under construction, bridges with newly installed countermeasures, and bridges judged to be "low risk" during the Stage II evaluations. All 165 of the scour critical bridges thus became the focus of the Department's Plan of Action, which is described in the next section.

During Stage II, revisions to the FHWA coding for the Structure Inventory and Appraisal (SI&A) for Item No. 113 were also finalized. All the scour susceptible bridges had been coded as "6", "U", or "T" during Stage I, which left their status as yet to be determined. During Stage II, the codings were updated, and any bridge with a rating of 3 or less was considered scour critical.

2006-Present: Plan of Action for Scour Critical Bridges

In August 2006, the Department issued a Plan of Action Report for the State bridges determined to be "scour critical" during the Stage II Evaluation. The original goal of the Plan was to install properly designed countermeasures at all scour critical structures, and, in some cases, to completely replace the bridge. However, recognizing that corrective work would need to be done over a period of many years, the Plan also prescribed a new real-time monitoring program for scour critical bridges during significant storm events to help safeguard the traveling public until corrective work was completed (this is in addition to regular NBIS inspections that evaluate the conditions of all State bridges).

The key components of the Department's 2006 Plan of Action are listed and briefly described below:

- *Establishment of a "Scour Critical" State Watch List* – The Plan established a watch list comprising the 165 bridges determined to be scour critical during the Stage II In-Depth Evaluation. These will be monitored during flood events until corrective action is completed.
- *Analysis of the Types and Costs of Countermeasures* – The Plan identified preferred countermeasure methods to remediate the State's scour critical bridges, including stone riprap, rock-and-wire (gabion) mattress, concrete slabs, and articulated concrete block. Unit costs were developed for each countermeasure method, and the average construction cost per bridge was estimated to be $298,000. The Plan cites two major hurdles to installing countermeasures: (1) approval of environmental permits; and (2) the acquisition of right-of-way easements.
- *Correlation of Water Management Areas, Stream Gaging Stations, and Watch List Bridge Locations* **–** The Plan developed a methodology to evaluate real-time data from streams and watersheds in order to determine threshold values when site monitoring will be required. The State is divided into 20 Water Management Areas (WMA) which are separated by natural watershed boundaries. Each WMA exhibits similar environmental characteristics within its boundaries, and all are managed by the NJDEP. The USGS manages a network of surface-water gaging stations throughout the WMAs which provide "real-time" stream level data through satellite, radio, and telephone telemetry. These real-time data are posted every 1 to 4 hours on the USGS Internet site. Seven USGS gages were found to be located near bridges on the Watch List, and the Action Plan correlates these gauge sites with the WMAs and Watch List bridges. The Plan also provided a correlative sorting by County and NJDOT Maintenance Region.
- *Development of a Vulnerability Index to Prioritize Bridges to be Monitored* - Since storms sometimes encompass large geographical areas, it may not always be possible to monitor all Watch List bridges simultaneously with available Department personnel resources. Thus, the Plan of Action prescribes a system to rate and rank each bridge according to its potential vulnerability to scour damage. Unlike previous prioritization schemes that considered the importance of the structure to the transportation network, the Vulnerability Index focuses only on factors specifically related to scour, e.g. Foundation Type, Existing Scour Problems, Streambed Material, History of Debris. The Vulnerability Index analysis in the Plan ranked 17 bridges as "High", 101 bridges as "Moderate," and 47 bridges as "Low."

- *Establishment of a Procedure to Monitor Watch List Bridges during Floods* – The Plan establishes a procedure for real-time monitoring of scour critical bridges during flooding events. The first indication of a potential monitoring situation will be a flood warning posted by the National Weather Service (NWS). This will prompt the Department's Structural Evaluation Group to begin tracking the USGS gages for the affected storm area on the Internet. The "trigger" to commence scour monitoring is the observation that a particular stream gauge or possibly an entire watershed has reached a critical flood stage. Control will then transfer to the Department's Operations Group, and the following sequence of actions will take place:

    - The Operations Group will dispatch field crews to perform inspection monitoring of the scour critical bridges within the flood prone area utilizing a list of bridges previously provided by the Structural Evaluation Group.
    - The dispatched field crew will observe and assess the affected bridges by completing a standard inspection monitoring form that addresses both "critical" and "non-critical" items. To aid in their field monitoring, the field crew will utilize prepared sheets for each bridge that describe the key data related to scour including projected scour depth, substructure and foundation type, and history of scour problems and debris.
    - When the field crew determines that closure of a bridge may be warranted, the approach described in the Department's Bureau of Structural Engineering Emergency Condition Procedures is to be followed. This gives the actual authority for closure to the Manager of Structural Evaluation and the Regional Maintenance Engineer, although the field monitoring crew can perform an emergency closure while waiting for the formal decision if they deem it necessary.
    - Before any closed bridge can be reopened, a post event inspection of the structure following the Department's normal NBIS procedures will be required. The Structural Evaluation staff will be responsible for determining if any repairs or scour countermeasures are required, as well as when a bridge can be safely reopened to traffic.

Program Highlights and Current Status

As the Department continues to implement the Plan of Action for the State's scour critical bridges, there are several recent developments that merit highlighting. These are briefly summarized below along with the status of New Jersey's Scour Program.

Erosion Monitoring of Selected Bridges by the United States Geological Survey (USGS)

The Department engaged the USGS New Jersey Water Science Center to perform erosion monitoring at selected bridges on the Scour Critical List. The bridges were all located along watercourses considered by NJDEP to have high environmental sensitivity. These bridges also had no history of significant field scour and were placed on the list solely based upon predicted scour using HEC-18 methods. The idea was to accumulate actual erosion and hydrologic data for each of the bridges. In the meanwhile, the field monitoring was being used as a substitute method of countermeasure.

In April 2008, the USGS commenced erosion monitoring at eight bridges. The program was extended in late 2009 to a total of 13 bridges. Monitoring at each site consisted of: (1) a full time, real time stream flow gauge; (2) periodic depth and water velocity surveys utilizing a fathometer; and (3) a topographic survey of stream cross sections upstream, downstream, and at abutment faces on quarterly basis. Over a period of five years, the erosion monitoring program yielded valuable data, which is currently being used to evaluate the scour risk of these bridges. The Department concluded the erosion monitoring contracts in 2014.

Impact of Environmental Permits and Right-of-Way Easements

One major challenge to implementing the Plan of Action has been timely approval of NJDEP environmental permits. The two major issues with environmental permitting have been: (1) reducing disturbance to the stream during construction activities; and (2) allowing passage of fish on both a short term and a long term basis (NJDEP, 2008). Environmental concerns are most critical for streams where trout are present. Lengthy approval times and occasional denials have been encountered for certain bridges on the Watch List. It is noted that articulated concrete blocks (ACBs) are emerging as a preferred countermeasure method for reducing environmental impact.

Another challenge in implementing the Plan of Action has been the acquisition of right-of-way easements. Since installed countermeasures typically extend beyond the bridge limits, right-of-way acquisition is required at locations where the existing property line is at the edge of the parapet. Temporary easements may also be needed to allow access to the streambed during construction. While easements are almost always assured, the process is tedious and requires considerable lead time.

Status of State's Scour Critical Bridges

Since 2006, the Department has made progress in implementing the Plan of Action for bridges on the State Watch List. The status of the original 165 bridges designated as "scour critical" is as follows:

Bridges on Original Scour Critical List	165
Bridges Reanalyzed and No Longer Scour Critical	–13
Bridges with Countermeasures Construction Completed	–10
Total Remaining on Scour Critical List	142

At present, the countermeasures design and construction program is largely inactive pending the results of this research study and the USGS Erosion Monitoring program. Of the remaining 142 bridges on the Scour Critical List, the following is a summary of their status:

Bridges with Countermeasures under Construction	7
Bridges Undergoing Erosion Monitoring	+ 13
Other Bridges on Scour Critical List	+ 122
Total Remaining on Scour Critical List	142

A principal objective of this research study is to develop a new scour evaluation procedure that will allow the Department to discern more precisely those bridges which are scour critical. Although POAs were previously developed for all the State's scour critical bridges, some of the POAs will be modified as these bridges are revisited and reevaluated using SEM. Likely modifications will range from removal from the State's Scour Critical List to an increase in priority for installation of protective measures.

Recent Super Storms Provide Opportunity for Improved Scour Evaluation

Two recent super storms, Hurricane Irene and Tropical Storm Sandy, have created an opportunity to obtain real scour data associated with these rare flood events. Many streams throughout the state have now experienced flows close to or in excess of 200 year events as a result of these storms. It is noteworthy that the only major bridge failure occurred in a tidal area (this research study does not address tidal area bridges). So, it is an opportune time to re-inspect the inland scour critical bridges and reanalyze their scour susceptibility.

A new companion study is planned to assess the impact of these super storms on the stream beds and related scour for the State's bridges. This "Implementation Phase" will analyze selected bridges using both the Scour Evaluation Model (SEM) and the envelope curve method, which will add yet another degree of confidence to the research study.

SURVEY OF SCOUR PRACTICE

Survey Methodology

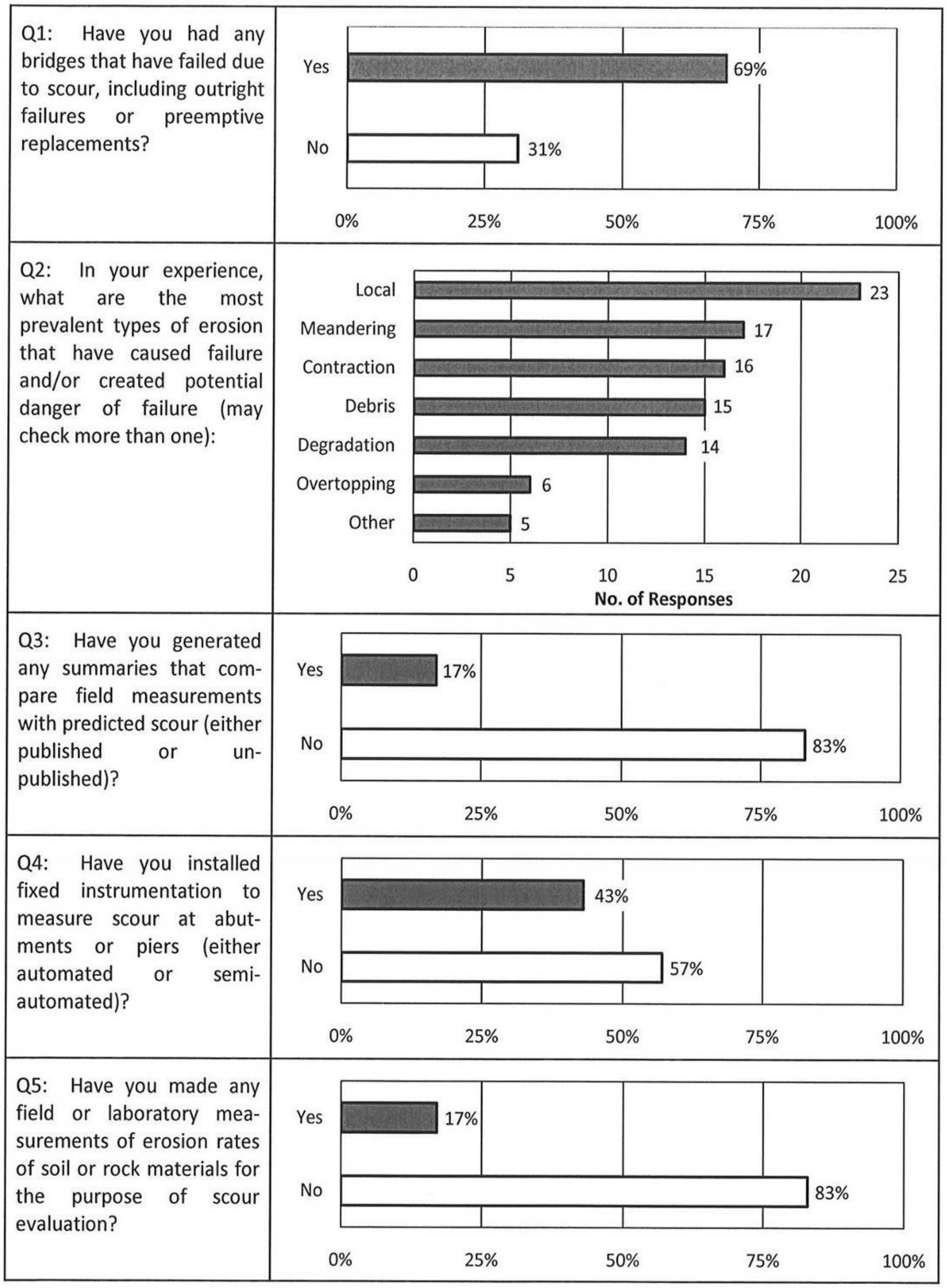
During the summer of 2009, a Scour Practice Survey was conducted to assess the varied scour design and evaluation methods used by transportation agencies within the U.S. and Canada. The survey objectives were threefold: (1) to compile an updated summary of scour practice as related to HEC-18; (2) to investigate modified or alternative methods for estimating scour depth; and (3) to identify potential best practices that might be adopted in New Jersey.

The ten-question survey was developed in cooperation with the Scour Project Implementation Committee, and it was administered by the NJIT Research Team. The survey queried agencies about scour design standards, experiences with failures, monitoring programs and countermeasure preferences, among other issues. The graphical interface of the survey was designed to be functional, attractive, and user-friendly. In an effort to maximize response rate, participants were given the choice of several response modes, including direct on-line (to a server), email attachment, mailed hard copy, or any combination of these. Respondents were also encouraged to forward document files and web links describing local scour practice. Electronic responses were accumulated in a Microsoft Access database located on the server of NJIT's Transportation Research Center. A copy of the Web-based Scour Survey and Email Transmittal is included in **Appendix B5**.

NJDOT distributed the survey to all the State Bridge Engineers via the AASHTO Bridge Committee email network in late July 2009. Reponses began to accumulate on the NJIT server immediately. Over the next 60 days, response to the Practice Survey was notably strong with a total of 35 responses received, representing a nearly 70 percent response rate. Some respondents also forwarded failure data, photos, and design standards and specifications. The authors believe that the favorable response rate reflects, in part, a growing desire by states to seek alternatives for the analysis tools in HEC-18.

Survey Results

The results of the Scour Practice Survey are summarized in **Figure 1**. The first question serves to confirm the breadth of the scour problem nationally, with 69 percent of agencies responding that they have had bridges fail due to scour, either by outright failure or by preemptive replacement. The most common type of scour erosion reported in the survey was local (23 responses), followed by meandering (17), contraction (16), debris (15), and degradation (14). Overtopping was reported by only six agencies as a problem. About 40 percent of the respondents indicate that they have installed fixed instrumentation to measure scour at abutments or piers, while only 17 percent have actually generated any summaries that compare predicted scour with field



Q1: Have you had any bridges that have failed due to scour, including outright failures or preemptive replacements?	Yes 69% No 31%
Q2: In your experience, what are the most prevalent types of erosion that have caused failure and/or created potential danger of failure (may check more than one):	Local 23 Meandering 17 Contraction 16 Debris 15 Degradation 14 Overtopping 6 Other 5
Q3: Have you generated any summaries that compare field measurements with predicted scour (either published or unpublished)?	Yes 17% No 83%
Q4: Have you installed fixed instrumentation to measure scour at abutments or piers (either automated or semi-automated)?	Yes 43% No 57%
Q5: Have you made any field or laboratory measurements of erosion rates of soil or rock materials for the purpose of scour evaluation?	Yes 17% No 83%

Figure 1. Summary of Scour Practice Survey Results

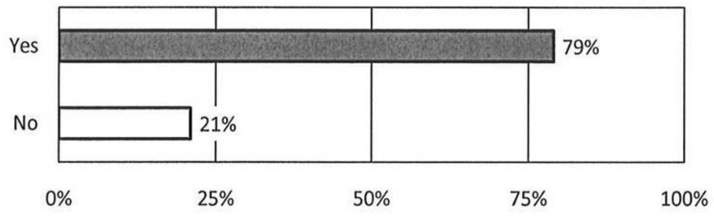
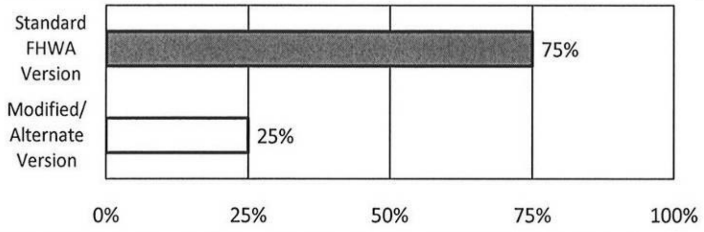
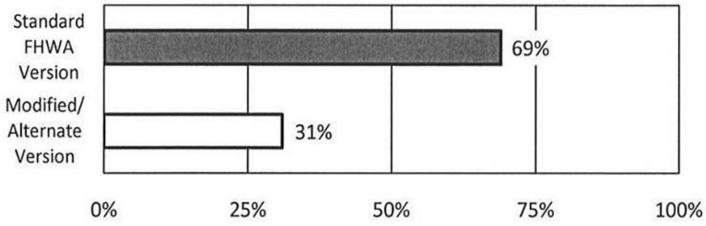
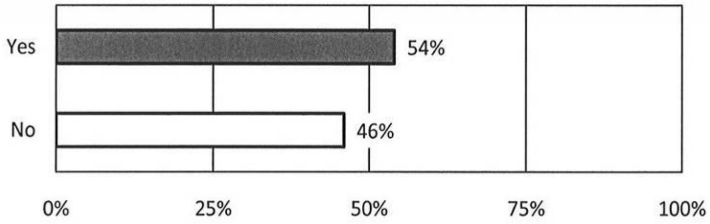
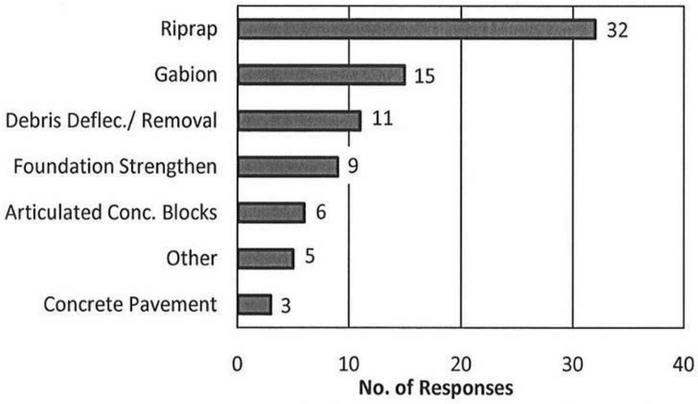
Q6: In the light of your experience of different types of bridge scour, is there a need to modify current HEC-18 design procedures?	
Q7: What scour procedures and equations do you use in the design of **new** bridges?	
Q8: What scour procedures and equations do you use in the evaluation of **existing** bridges?	
Q9: Do you consider the effects of natural armoring in your scour computations?	
Q10: Does your agency have a preference for particular kinds of scour countermeasures? (may check more than one)	

Figure 1. Summary of Scour Practice Survey Results (continued)

measurements. A similar number of agencies report that they have undertaken either field or laboratory measurement of erosion rates for soil or rock materials.

Among the most interesting results of the survey was the response to Question 6, which asked whether there was a need to modify HEC-18 design procedures. An overwhelming 79 percent of the agencies responded in the affirmative. Consistent with this response, 9 agencies indicate that they are now using modified or alternative scour analysis methods for new bridges, while 11 states indicate that they employ modified/alternative analysis methods for existing bridges.

The final two questions provide insight about natural and artificial scour protection means in use. Slightly over half (54 percent) of the agencies consider the effects of natural armoring in their scour computations. Natural armoring occurs when a residual layer of coarse particles is exposed on the stream bed due to erosion and removal of fines. With regard to scour countermeasures, riprap remains the preferred choice by more than a 2:1 ratio. Gabions, debris deflection/removal, and foundation strengthening were the next most applied countermeasure methods. A small minority of the agencies report use of articulated concrete blocks, concrete pavement, or “other” methods.

A project-related technical paper was presented during the 5th International Conference on Scour and Erosion (ICSE-5) in San Francisco on November 7-10, 2010 (Schuring et al, 2010). The paper focused on the results of the Scour Practice Survey and also described the ongoing scour research in New Jersey. Conference attendees included transportation officials, scour practitioners, and scour researchers from across the U.S. and around the world. Positive feedback was received on the Practice Survey, as well as New Jersey’s scour research initiatives.

Selected Best Practices of Other States

The Scour Practice Survey clearly showed an increasing concern by State agencies that the procedures in HEC-18 do not necessarily correlate well with field observation of scour. These agencies are seeking more realistic procedures to estimate scour depth, since resources for construction and repair are chronically limited, and bridges need to be better prioritized so that funds are expended where they are truly needed.

A number of states furnished supporting documentation for their modified or alternate scour analysis methods. Included were published formal design standards and/or rigorous scientific studies supporting their deviations from the standard methods in HEC-18. In other cases, the method changes were internal agency directives only. Examples of such modified or alternate scour analysis methods are listed and described in **Table 1**. Reference links are also provided where available.

A review of the **Table 1** shows that transportation agencies have undertaken a wide variety of modified approaches. Some states such as Connecticut and Illinois have chosen to revise existing HEC-18 relationships by modifying factors of safety. Other states have developed entirely new scour evaluation procedures, such as South

Carolina (envelope curves) and Texas (bridge scour assessment levels). Pennsylvania is one of very few states to devise a method that addresses scour in channels lined with bedrock or very coarse soils (e.g. cobbles and boulders). It is noteworthy that Pennsylvania reports zero failures due to scour since implementation of their modified method in 1982.

Table 1 – Examples of Modified or Alternative Scour Evaluation Methods

State	**Method Description**
Alabama	This USGS Scientific Investigations Report published in 2008 provides an alternate method to assess scour depth in the Black Prairie Belt soil, a consolidated, highly cohesive, organic clay within Alabama's Coastal Plain. Envelope curves are presented based on observations of clear-water contraction scour at 25 bridge sites. The key explanatory variables were determined to be channel contraction ratio and velocity index (Lee and Hedgecock, 2008). Related Link: http://pubs.usgs.gov/sir/2007/5260/
Alberta	In Alberta, the procedure to evaluate existing bridges for pier scour allows use of the classic relationship: Scour Depth = 2 X Pier Width. For new bridges pile foundations are used exclusively for any foundation element in channel (New Jersey Institute of Technology, 2009).
Connecticut	Connecticut reduces the factor of safety of the Froehlich equation from +1 to +0.05. The modified relation represents the 50th percentile of LABORATORY scour data. This yields an "amended scour depth." The design manual further directs use of engineering judgment and all other relevant factors in determination of scour depth (Connecticut Department of Transportation, 2000). Related Link: http://www.ct.gov/dot/lib/dot/documents/ddrainage/9.B.pdf
Florida	Florida DOT published an entire Bridge Scour Manual to provide state-wide scour guidelines. The manual's 'FDOT Methodology' for clear-water and live-bed scour processes was included in the 5th edition of HEC-18. The methodology consists of a systematic approach for determining the estimated scour depth to effective pier width ratio. In addition, the manual includes a section on complex pier geometries and discusses aspects of contraction scour (Florida Department of Transportation, 2010). Related Link: http://www.oea-inc.com/FDOTScourManual_March2010.pdf
Illinois	Illinois DOT permits reductions in scour depth computed by HEC-18 methods for bridges founded in cohesive soil or rock. Such reductions are graduated from 0 to 100%, depending on the strength of the soil or degree of lithification of the rock. Any reduction must be supported by geotechnical investigation and substantial engineering judgment (Illinois Department of Transportation, 2009). Related Link: http://www.dot.state.il.us/bridges/brmanuals.html
Indiana	Indiana DOT advises consultants to use only the 100-year flow when evaluating existing bridges for rehabilitation (ignoring 500 year flow). The thinking is that an existing bridge has already served a percentage of its life, and the ultraconservative 500 year requirement is not needed. This is an unpublished guideline based on an "internal use document."

Table 1 – Examples of Modified or Alternative Scour Evaluation Methods (continued)

State	**Method Description**
Maine	This USGS Water Resources Investigations Report collected and analyzed pier-scour data for nine high river flows at eight bridges across Maine over a 4 year period. Observed maximum scour depths ranged from 0.5-12 ft., and were compared with predictions using the CSU equation in HEC-18. The HEC-18 pier-scour equations performed well for rivers in Maine, and MaineDOT uses them for evaluation of existing and new bridges (Hodgkins and Lombard, 2002). Related Link: http://me.water.usgs.gov/reports/wrir02-4229.pdf
Pennsylvania	PennDOT scour design method recognizes the variable erosion behavior of geologic materials in scour design. The standard establishes three classifications: sound bedrock, erodible bedrock and coarse soil (gravel, cobbles and boulders). Specific embedment depths and footing construction details are prescribed for each (Pennsylvania Department of Transportation, 2009). Related Link: ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%2015M.pdf
Maryland	Maryland SHA has developed a program known as ABSCOUR that is based on HEC-18 Equations with certain modifications to account for distribution of flow under the bridge, bridge geometry, and computation of velocity at the bridge abutments. ABSCOUR computes both clear water and live bed scour and selects the appropriate scour type based on the input information (Maryland State Highway Administration, 2007). Related Link: http://www.gishydro.umd.edu/sha_sept07/CH%2011%20SCOUR/3%20CH%2011%20APP%20A%20PART%20II.pdf
South Carolina	A recently published USGS Report of Investigation extends the earlier 2006 USGS study described above in “Comparative Scour Studies.” It recommends use of envelope design curves to estimate scour depth for South Carolina bridges. The curves are rigorously justified with field observations and measurements (from SC and elsewhere), as well as laboratory data (Benedict and Caldwell, 2009). SCDOT has already incorporated the envelope curves into their latest scour design standards (South Carolina Department of Transportation, 2009). Related Links: http://pubs.usgs.gov/sir/2009/5099/ http://www.scdot.org/doing/pdfs/requirements2009.pdf
Texas	This comprehensive study performed by Texas Transportation Institute summarizes a new method to assess a bridge for scour. It uses three levels of bridge scour assessment (BSA 1, 2, & 3) and erosion classification charts. The study also provides hydrologic and hydraulic computer programs to generate flow velocities for Texas rivers. Scour vulnerability is determined by comparing the predicted scour depth with the allowable scour depth of the foundation. The method is relatively simple to apply, and it overcomes some of the over-conservatism in current methods (Briaud et al, 2009). Related Link: http://tti.tamu.edu/documents/0-5505-1.pdf

REVIEW - TRADITIONAL & ALTERNATE METHODS OF SCOUR ANALYSIS

Overview of HEC-18 Scour Equations and Sources

FHWA Publication Hydraulic Engineering Circular No. 18 (HEC 18) has been a key companion resource for FHWA's national scour program. Now in its 5th edition, HEC 18 remains in wide use by transportation agencies and consultants. The original edition was launched relatively quickly in response to the Schoharie Creek Bridge collapse in 1987 to provide professionals with some basis for determining whether a bridge is scour critical.

Without question, HEC-18 is serving a worthy function in the nation's scour safety program by providing agencies and consultants with access to a compendium of design relationships. However, HEC-18 was never meant to be a mandate, but rather a guidance document that describes the "state of knowledge and practice." It does not preclude a transportation agency from applying another method of scour prediction as long as it is rational and defensible. A number of states have now opted to either modify the methods in HEC-18 or develop entirely new, alternate approaches for scour evaluation. Some of these were previously described in report section, "Selected Best Practices of Other States" in chapter, "SURVEY OF SCOUR PRACTICE" on page 19.

The scour design relationships contained in HEC-18 are an amalgamation of work by various investigators. As a starting point for modifying the Department's method of scour analysis, the Research Team revisited many of the original source documents cited in HEC-18. The results of this review are presented in this section.

Several contraction scour relationships are contained in the 5th edition of HEC-18. The equations cover situations for live-bed and clear-water scour phenomena in riverbeds with particulate materials, as well as for cohesive bed material (Laursen 1960 and 1963, Briaud et al. 2011).

Many new equations for pier scour are recommended in the expanded 5th edition of HEC-18. The principal design relationship for estimating pier scour is the "HEC-18 pier scour equation." It is based on the CSU equation and was derived from laboratory data by researchers at Colorado State University (Richardson, Simons, and Lagasse, 2001). This relation considers the effects of pier shape, angle of attack and bed conditions. Factors exist for wide piers and armoring, but the armoring factor, while not included in the 5th edition of HEC-18, is mentioned as viable. The Florida DOT methodology should be considered as an alternative to the HEC-18 equation, particularly for wide piers (FDOT 2011). Equations are also included that address pier scour in non-uniform bed materials, quarrying and plucking, and bedload abrasion in rock (Guo et al. 2012; Annandale 2006; Keaton et al. 2011). Additionally, an equation for cohesive materials was recommended from the Scour Rate In Cohesive Soil – Erosion Function Apparatus (SRICOS-EFA) paper published by Texas A&M University (Briaud et al. 2011). Other relationships developed from laboratory flume testing are also cited but not specifically recommended, e.g. Laursen (1980), Jain and Fischer (1979), Johnson and Torrico (1994).

For abutment scour, the principal relationship for many years was the Froehlich Equation, which is based on a regression analysis of 170 laboratory flume tests (Froehlich, 1989). The other alternative was the HIRE equation, which was originally developed from field data for scour at the end of spurs on the Mississippi River (Richardson, Simons, and Lagasse, 2001). The new relationship in the 5th edition is the NCHRP 24-20 equation (Ettema et al. 2010). This equation addresses both live-bed and clear-water situations and does not rely on the often difficult to determine parameter embankment length. The applicability of 24-20 appears to be promising. Other methods beyond these recommended relationships are also described, including many methods based on laboratory flume testing.

In addition, HEC-18 cites published studies for a variety of special cases of pier scour. Included are approaches for dealing with complex pier foundations (e.g. Salim and Jones, 1995), pressure flow conditions (e.g. Arneson and Abt, 1999), debris accumulation (e.g. Melville and Dongol, 1992), and skewed pier columns (e.g. Raudkivi, 1986).

The review of HEC-18 has revealed certain limitations that, in the opinion of the Research Team, must be addressed to develop a comprehensive scour standard for New Jersey. These are listed and briefly described below:

- Many of the HEC-18 relationships are not sensitive to the broad range of soil and rock textures actually encountered at bridge sites. Thus, there has been a tendency by some practitioners to “force fit” HEC-18 equations to a bed sediment even if it does not actually fall within the usable range of the relationship. This phenomenon is sometimes exacerbated by the complexity of some of the newer equations. Unfortunately, this has led to an over-prediction of scour depth in many situations.
- Bed sediments consisting of very coarse granular particles, e.g. cobbles and boulders and bedrock were not addressed in the earlier editions of HEC-18. Such sediments are common in mountainous regions and certain glaciofluvial environments, both of which occur in New Jersey. These typically exhibit high resistance to erosion and low susceptibility to scour. The 5th edition now addresses some of these special geotechnical conditions, but there are still knowledge gaps.
- When evaluating the future scour potential of existing bridges, the actual field performance over time clearly plays a role. However, guidance for considering bridge longevity is limited in HEC-18.
- The practice of using envelope curves to predict maximum scour depth is increasing in the U.S. However, there is minimal treatment of envelope curves in the current edition of HEC-18.
- HEC-18 recommends that clay sediments be analyzed using the Scour Rate In Cohesive Soils (SRICOS) method (Briaud et al, 1999, 1999b, 2011) in

combination with the Erosion Function Apparatus (EFA), originally developed at Texas A&M University. While these are worthy tools for scour research or for designing major bridge structures, their use for scour evaluation of many routine State bridges is not practical.

In addition to the limitations of the HEC-18 methods described above, the Research Team discovered another factor that affected the analyses as to whether or not a bridge was scour critical. The majority of Stage II studies did not satisfactorily characterize the grain size of the stream bed materials on account of inadequate sampling methods. This caused a bias towards finer grain sizes in at least half of the bridges studied. The grain size bias had the effect of compounding, even further, the degree of conservatism already built in to some of the HEC-18 relationships. The end result is that a number of bridges were mistakenly determined to be scour critical.

The review of HEC 18 methods in combination with the errors in sediment characterization led in part to the decision to develop a new scour standard for New Jersey. Known as the Scour Evaluation Model (SEM), it provides standard methods and protocols for geotechnical evaluation of scour risk. SEM is fully described in chapter, “NEW JERSEY SCOUR EVALUATION MODEL (SEM)” on page 61.

HEC-18 Hydrologic and Hydraulic Requirements for Scour Evaluation

An essential parameter in the design of a new bridge or evaluation of an existing bridge to resist scour is the magnitude of the design flood. The 5th Edition of HEC-18 has increased the recommended scour design floods for new bridges designed for a 100-year flood from a 100- to a 200-year flow event as shown in **Table 2** below. The table also summarizes the latest criteria for hydraulic design and scour countermeasure design.

For existing bridges, the scour design flood for evaluative purposes with respect to critical status remains at a 100-year flow event. However, if countermeasures are required to protect the bridge, they shall be designed for a 200-year standard. FHWA mandates that once a bridge has been determined to be scour critical, the bridge must be monitored and/or corrective measures implemented. Measures that can remove a bridge from the scour critical list include bridge replacement or installation of protective countermeasures. Note that FHWA does recognize long term monitoring as an acceptable countermeasure for bridges determined to have the lowest consequence of failure (COF) and/or low average daily traffic (ADT). However, a bridge with monitoring countermeasure shall retain its scour critical code.

A principal motivation for the current research project was to develop a more discerning scour evaluation procedure to assure that bridges on the scour critical list are actually critical. For example, the Research Team found numerous inconsistencies in the hydraulic and hydrologic analyses of the Stage II studies for the bridges on the scour critical list. As an example, stream discharges were developed using many different methodologies (e.g. extreme value, regression analysis), as well as data from different agencies (e.g. FEMA, USSCS, USGS). The inconsistencies led in part to the decision to develop a new scour standard for New Jersey. Known as the Scour Evaluation Model (SEM), it provides a standard procedure for the hydrologic and hydraulic evaluation of scour risk.

Table 2 – Hydraulic Design, Scour Design, and Scour Design Countermeasure Design Flood Frequencies (Table 2.3 from Arneson et al, 2012)

Hydraulic Design Flood Frequency (Q_D)	Scour Design Flood Frequency (Q_S)	Scour Countermeasure Design Flood Frequency (Q_{CM})
Q_{10}	Q_{25}	Q_{50}
Q_{25}	Q_{50}	Q_{100}
Q_{50}	Q_{100}	Q_{200}
Q_{100}	Q_{200}	Q_{500}

Comparative Studies of Observed vs. Predicted Scour in the U.S.

Over the last decade, several studies have compared the field scour observed at bridge sites with the scour values predicted by various equations. The studies reflect the ever increasing concern that current methods for estimating scour depth are principally based on laboratory experiments and do not necessarily correlate well with field conditions. Bridge owners and their consultants are seeking more realistic procedures to estimate scour depth, since resources for construction and repair are chronically limited, and bridges need to be better prioritized so that funds are expended where they are truly needed.

Three comparative studies of bridge scour will be summarized in this section. All studies were rigorous, and in total they comprise data from more than 200 bridges located in 5 states, and they examined the 6 most widely used predictive scour equations.

(1) Lombard, P.J., and Hodgkins, G.A. (2008). "Comparison of Observed and Predicted Abutment Scour at Selected Bridges in Maine." Scientific Investigations Report, U.S. Geological Survey, Reston, Va.

This insightful study was recently completed by the U.S. Geological Survey (USGS) in cooperation with the Maine Department of Transportation. The investigators analyzed 50 bridges that were distributed geographically throughout the State. The median age of the bridges was 66 years, and all were single-span with widths of opening ranging from 12.7 to 126 ft. In addition, all were located on non-tidal waterways and founded on erodible material as opposed to bedrock. Field surveys were conducted to determine channel geometry and characteristics, as well as to measure observed abutment scour, which ranged from 0 to 6.8 ft. Skew angles of the abutments and embankments in relation to the channel showed wide variation, ranging from 0 to 50 degrees.

The four scour estimation methods applied to the bridges in the Maine study were the Froehlich/Hire method, the Sturm method, the Maryland Department of Transportation method, and the Melville method. A summary of the study results comparing predicted and observed scour are presented in **Table 3**. As indicated, no significant correlation was found between calculated scour and scour observed in the field for any of the four methods (correlation coefficients ranged from -0.09 to 0.08). In fact, predicted scour was frequently an order of magnitude greater than observed scour. Scour was also underpredicted by the equations 4 to 14 percent of the time.

Given the lack of correlation between predicted and observed scour, the authors suggest it may be preferable for designers to prescribe a single value of maximum abutment scour of say 7 ft., the maximum field scour recorded in the study. Of course, such an approach would first require confirmation that a given bridge has similar site and structural characteristics to those of the study. Application of a factor of safety is also recommended. The authors note that the high median age of the bridges (66 years) and large sample size (200 abutments) provide statistical confidence in the study results from a hydrologic perspective.

Table 3 – Summary of Predicted vs. Observed Abutment Scour for Maine Study (modified from Lombard and Hodgkins, 2008)

Method	***Overpredictions***			***Underpredictions***			***Correl. Coeff.***
	%	**Avg (ft)**	**Max (ft)**	**%**	**Avg (ft)**	**Max (ft)**	
Froehlich	96	10.8	33.2	4	2.2	3.9	0.00
Sturm	86	8.4	50.9	14	5.5	17.7	0.01
MD DOT	89	11.8	200.3	11	1.2	3.0	-0.09
Melville	86	4.3	21.3	14	1.4	3.2	0.08

(2) Benedict, S.T, Deshpande, N., Aziz, N. M., and Conrads, P.A. (2006). "Trends of Abutment-Scour Prediction Equations Applied to 144 Field Sites in South Carolina." Open-File Report 2003–295, U.S. Geological Survey, Reston, Va.

In this study the U.S. Geological Survey (USGS) in cooperation with the Federal Highway Administration (FHWA) analyzed 144 bridges in South Carolina. Scour depth predictions were based on hydraulic conditions associated with 100-year flow at all sites and the flood of record at 35 sites. Median sediment size, D_{50}, was estimated by obtaining one or more grab samples from the channel bed at each bridge location.

Five published scour equations were used to analyze each substructure including the original Froehlich equation (with and without the +1 safety factor), the modified Froehlich equation (as modified by Richardson and Davis (2001)), the Sturm equation, the Maryland Department of Transportation equation, and the HIRE equation. In addition, an equation based on unpublished FHWA data and designated as the Young equation was also applied. A comparative plot of predicted and observed scour for the original Froehlich equation from the study is shown in **Figure 2**. This result is typical, leading the investigators to conclude that all five of the equations frequently over-predict scour depth, and at times excessively so. The study also developed an extensive digital database supporting data that is useful for evaluation of future scour relationships.

Interestingly, the investigators also report the results of an auxiliary study concerning the difficulty of obtaining representative samples of bed sediments for the purposes of estimating median grain size or D_{50}. In particular, for bridge sites in the Piedmont physiographic province, a high variability in grain size was observed within any given channel, even over small lateral distances. This result emphasizes the non-homogeneity of channel sediments, and the authors caution against the use of surface "grab" samples to characterize sediment grain size. They state that soil boring data is preferable since it better describes the composition and thickness of the various soil layers.

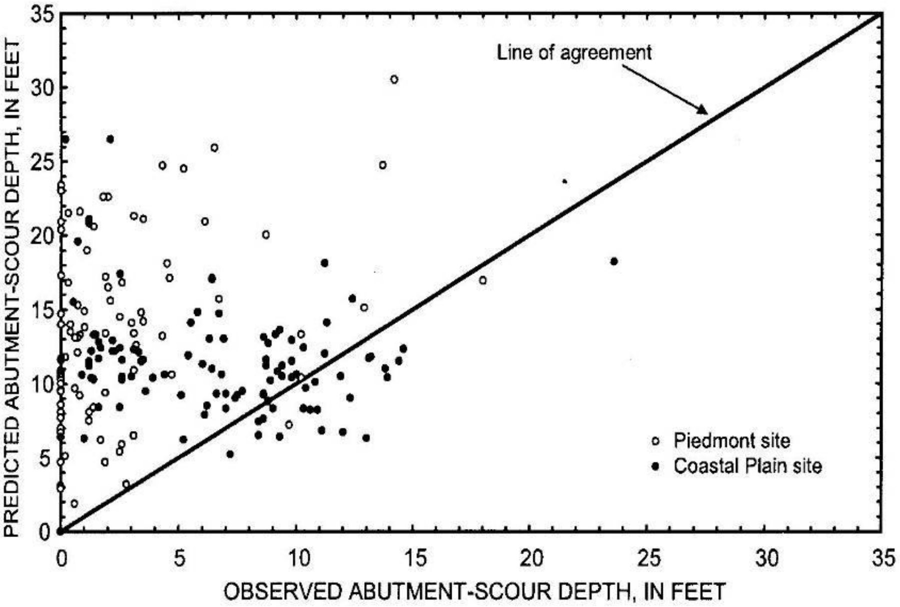


Figure 2. Observed vs. Predicted Scour for Original Froehlich (w/safety factor of +1) for South Carolina Study

(3) *Wagner, C.R., Mueller, D.S., Parola, A.C., Hagerty, D.J., and Benedict, S.T. (2006). "Scour at Contracted Bridges." Web-Only Document 83 (Project 21-14), National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.*

This comparative scour study was conducted under the National Cooperative Highway Research Program (NCHRP), and its focus was 15 bridge sites located in the states of Minnesota, Montana, and South Dakota. A combination of real-time and post-flood data was collected, and directional velocities were measured at some of the sites. The material properties of the streambed, stream bank, and floodplain were also described.

The four scour estimation equations applied to the study bridges included the Sturm equation, the Froehlich equation, the modified Froehlich equation, and the HIRE equation. Upon comparing the predicted with the observed scour depths, the authors conclude that all methods are unreliable. In most cases the scour equations over-predicted scour depths compared with those actually observed in the field, often by a factor of 2 to 40 times. However, under certain conditions, predicted scour depths were less than observed depth.

The authors cite the failure of laboratory research and one-dimensional models to capture the complexity of field conditions as the major reason for the unreliability of the predictive equations. In particular, channel alignment and channel bends are cited as having an appreciable influence on the depth and distribution of scour. The authors suggest that a simpler alternative approach to predict scour depth be considered, such as a use of regionally-based “envelope” design curves regressed from actual field scour measurements.

GEOTECHNICAL EVALUATION OF BRIDGE SCOUR

Background

This chapter provides guidelines for analyzing the scour susceptibility of geologic materials that support bridge substructures. The guidelines are tailored towards New Jersey's unique geologic regions and conditions. The methodologies presented herein reflect the state of practice for bridge scour and are compatible with Hydraulic Engineering Circular No. 18 (HEC-18) published by the FHWA (Arenson et al 2012), which provides a framework for states and other agencies to develop scour standards. Increasingly, transportation agencies across the U.S. are adopting their own scour standards to reflect past experience and address local conditions (e.g. PennDOT 2000, FDOT 2011, ILDOT 2008, TXDOT 2006 & 2009, SCDOT 2009).

It is widely acknowledged that different geologic materials scour at different rates for equivalent hydraulic conditions (e.g. FHWA 2001; NCHRP 2003). Geotechnical properties that can influence scour rate include particle diameter, particle shape, size distribution, density, cohesion, stratification, and cementation. Most scour relationships in HEC-18 are based on laboratory flume studies conducted with sand-sized sediments, which has led to overly conservative predictions of scour depth at some bridges as compared with field scour observations. This is especially true where the stream bed consists of materials with increased scour resistance such as bedrock, boulder trains, and hard, cohesive soils. Such geotechnical conditions commonly occur in certain parts of New Jersey as will be described in the next section (See report section, "Summary of New Jersey Geology with Comments on Scour Potential" on page 30). It is therefore prudent to consider the specific properties of the supporting geologic materials in order to develop realistic predictions of scour depth.

The majority of this research study was conducted when HEC-18, 4th edition (Richardson and Davis 2001), was the prevailing guidance document. This edition contained very limited guidance for analyzing scour in some of the geologic conditions present in New Jersey, such as bedrock, boulder trains, and hard cohesive soils. The Research Team developed new methods for dealing with these special conditions for the State's bridges. With subsequent publication of the 5th edition in 2012, new guidance became available for a wider range of geotechnical conditions, and the geotechnical guideline presented in this chapter now incorporates selected HEC-18 methods appropriate for New Jersey geology and bridges.

This guideline focuses principally on evaluating scour risk of existing bridges, but many model components are useful for designing new bridges as well. In general, the geotechnical scour risk is determined by the kind of geologic material present in the streambed. For existing bridges, performance history is also a significant factor in predicting scour depth, particularly for older bridges. The fact that a bridge has performed satisfactorily for many decades demonstrates that the foundation materials have shown scour resistance when subjected to multiple record storms. Also, an older bridge nearing the end of its design life will normally be replaced in a matter of a few decades or less. Thus, the scour risk and standards for an existing bridge will be different than a new bridge in similar geologic conditions.

Note that this guideline does not address all possible geotechnical conditions that might be encountered at bridge sites within the State. It is further noted that there are gaps in existing knowledge of scour behavior. **Therefore, sound engineering judgment shall be applied to all scour evaluations, as required.** The designer is also encouraged to investigate the performance of existing bridge structures at the same location or at nearby locations on the same stream.

Summary of New Jersey Geology with Comments on Scour Potential

New Jersey is divided into four physiographic provinces: Valley and Ridge, Highlands, Piedmont, and Coastal Plain (See **Figure 3)**. Each province exhibits unique geology, landforms, and terrain. These characteristics, in turn, influence the scour behavior of bridges located in the respective province. The following narrative provides a brief description of the State's physiographic provinces. Also included are comments about the influence of province geology and geomorphology on general scour behavior. This is because stream channels within the different provinces often respond differently to similar hydrologic events. Please note that these are regional trends, and they are provided as a general guideline only. Each bridge site must still be investigated using the evaluation procedure described in the next chapter section.

Valley and Ridge**:** The Valley and Ridge province, located in the northwest corner of the State, is also known as the Folded Appalachians. It is mostly underlain by sandstone, shale, limestone, and conglomerate bedrock. The topography is characterized by high, steep ridges composed of resistant sandstone and conglomerate, separated by wide valleys underlain by weaker shale and limestone. The entire province has been glaciated, so there are substantial surface deposits of till and outwash throughout, especially in valley areas.
<u>Scour Potential</u>: The channel sediments in most river systems are glaciofluvial sands, gravels, cobbles and boulders, which typically become coarser with depth. Significant armoring action may therefore be expected, which can reduce scour depth. The mild gradient in some of the larger valleys can cause channel meandering, however.

Highlands**:** The Highlands province is located in the northern part of the State. It is an elevated, mountainous plateau dominated by ancient metamorphic and igneous rocks, including granitic-gneiss, granite, quartzite, and marble. The Highlands is the southernmost extension of the New England physiographic province. The terrain consists of rolling hills and low mountains with intervening valleys of varying widths. The northern section has been glaciated, so moderate thicknesses of till and glaciofluvial sediments are present. The glacial soils tend to be very coarse-grained having been derived from hard, crystalline rock. Residual soil and weathered bedrock dominate the surface deposits in the southern section of the Highlands, south of the Terminal Moraine. Here the texture of the geologic materials ranges more widely from clay size all the way up to boulders (residual "core" stones).

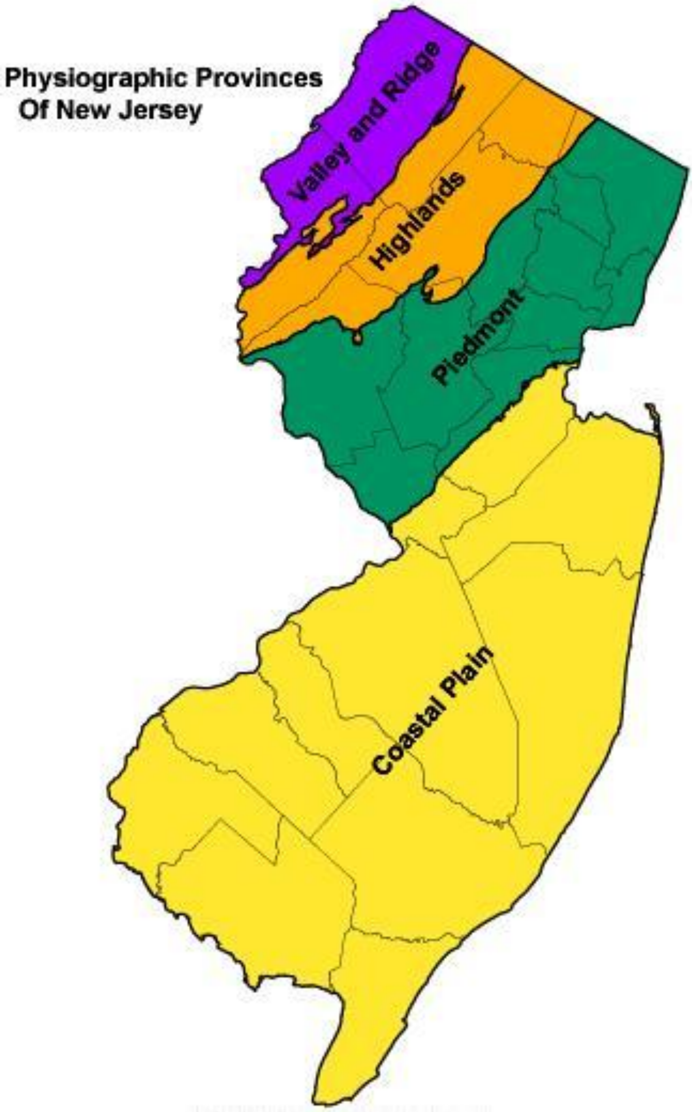


Figure 3. Physiographic Provinces of New Jersey (NJGS, 2011)

Scour potential: In the northern Highlands many streams have moderate to steep gradients, so bed sediments are often very coarse, and bedrock may be encountered at relatively shallow depths. Such bed materials are often highly scour resistant, although long term downward channel erosion may need to be examined in some cases. The residuum in the southern Highlands may contain moderate amounts of silt and clay, which are more susceptible to scour. However, river gradients are more moderate in this section, and boulder trains are encountered in some streams.

Piedmont: The Piedmont physiographic province, also known as the Newark Basin, forms a wide band that extends from the State's northeast corner to the west central boundary. The province is underlain by gently dipping *red beds* consisting of mudstone, sandstone, and shale. Mostly, the topography is gently rolling, although long, steep ridges of resistant basalt and diabase traverse the province from northeast to southwest (the *Watchungs* and the *Palisades*). Residual soil and weathered bedrock overlie the

majority of the Piedmont, although the northern section has been glaciated and contains a veneer of till and outwash, as well as two vast glacial lakes (*Hackensack Meadowlands* and *Great Peace Meadows*).
Scour potential: The upper alluvium of many streams consists of medium to fine textured sediments, including sand, silt, clay, and gravel. These soils may exhibit medium to high scour potential. However, at some locations, the alluvium is underlain rather shallowly by mudstone, sandstone, or shale, which typically exhibit good scour resistance. Also note that streams in the glaciated northern Piedmont or in the vicinity of the Watchung or Palisades ridges may contain cobble and boulder trains of scour resistant rock.

***Coastal Plain*:** New Jersey's Coastal Plain covers the southern half of the State. It is an area of relatively flat topography, underlain by unconsolidated sediments of Cenozoic and Cretaceous age. The predominant surficial material in the southern Coastal Plain is sand, while the northern sections contain considerable deposits of clay, silt, and glauconite (greensand).
Scour potential: The sands of the southern section can exhibit significant scour under the right hydrologic conditions. Conversely, the medium and stiff clays encountered in the northern section are often hard and strongly cohesive, so scour potential is reduced. The mild stream gradients throughout can cause channel meandering at some locations.

Description of Erosion Classes

While it is widely acknowledged that different geologic materials scour at different rates, many scour analysis methods do not adequately consider the geotechnical properties that actually control scour rate. For example, many of the HEC-18 design relations are based solely on contraction ratio or other geometric parameters and do not factor in geotechnical properties at all (Refer to discussion in report section, “Overview of HEC-18 Scour Equations and Sources” in chapter “REVIEW- TRADITIONAL & ALTERNATE METHODS OF SCOUR ANALYSIS” on page 22). And for scour relationships that do consider sediment characteristics, influence is often limited to a single property such as D_{50}. Such approaches ignore other geotechnical properties critical to scour behavior such as size distribution, density, cohesion, particle shape, stratification, and cementation.

A critical step in evaluating the scour potential geological materials in streambeds is classification. Several standard geotechnical classification systems are available, e.g. Unified and AASHTO. A limited number have been developed specifically for scour analysis, like the Simplified Texas Method (Briaud et al, 2009), which utilizes the Unified System. However, the method does not address streambeds containing extremely coarse granular materials like cobbles and boulders or bedrock of varying competencies. A classification system for cohesive soils presented in the 5th edition of HEC-18 (Fig. 6.11, source is Briaud et al 2011) is an improvement in that it extends applicability to cobbles and jointed rock. A disadvantage is that stream beds are rarely a single Unified group symbol, but rather a composite of two or more different groups.

To address perceived limitations in current classification approaches for scour analysis, it was decided to develop a new classification system for New Jersey bridges. The new Scour Evaluation Model (SEM) system for classifying the erosion resistance of streambed materials is summarized in **Figure 4**. It requires the user to classify the streambed materials at a bridge site into one of seven different erosion classes. The system has two principal advantages over previous classification schemes for scour applications. First, it is comprehensive and spans all geologic materials from weak soil to competent rock. This is essential in a state like New Jersey, which, in spite of its small size, contains an array of vastly different geological conditions. A second advantage of the system is that the classes are graduated and grouped according to erosion rate and scour risk, avoiding the necessity to choose a single soil type or group.

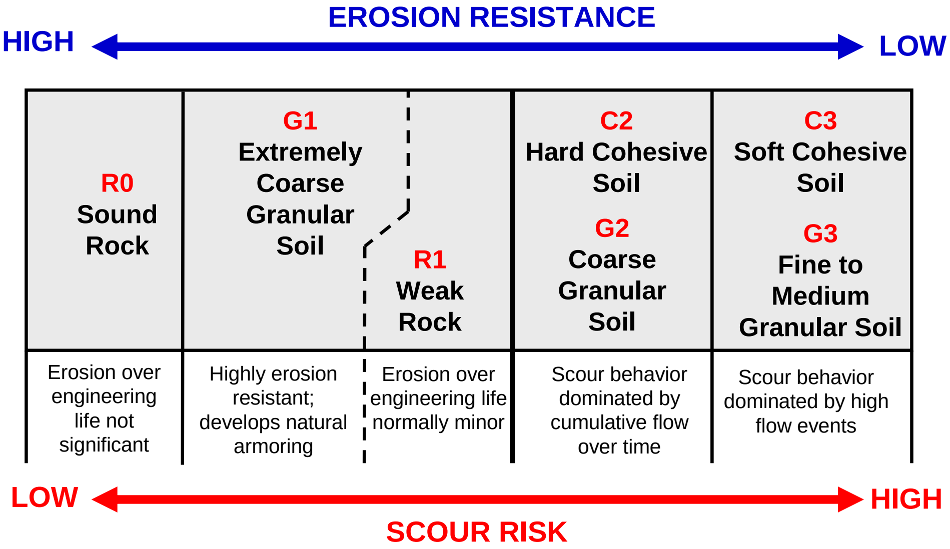


Figure 4. New Jersey SEM Erosion Classes for Soil and Rock

Definitions of the seven erosion classes in the SEM system are presented in **Table 4**. Each erosion class is defined using standard geotechnical indexes and tests, e.g. Unified System, ASTM Standards. Also included are notations about where the various erosion classes may be expected geographically within the State. While the SEM Erosion Class System was developed for New Jersey bridges, it is easily adapted to other states and physiographic regions.

Geological Materials with High Erosion Resistance

Certain kinds of geological materials exhibit high resistance to erosion by scour action. These include bedrock and coarse granular soil containing frequent cobbles and boulders. Such materials represent a low scour risk even at high flows.

R0. Sound Rock: This class shall include sound bedrock composed of granite, gneiss, basalt, diabase, dolomite, limestone, slate, siltstone, sandstone and related rocks.

Table 4 – Definition of SEM Erosion Classes

Erosion Class	Predominant Texture & Description[1]	Occurrence by Physiographic Province
High Erosion Resistance		
R0. **Sound Rock**	Rock of this classification shall be generally sound, although some fracturing and weathering may be present. Includes granite, gneiss, basalt, diabase, dolomite, limestone, slate, siltstone, sandstone, and related rocks. Extracted rock cores shall exhibit an average RQD[2] of 70%. Also includes mudstone and shale with the same RQD[2] and a Slake Durability Index (SDI)[3] of 90 or greater.	Highlands, Ridge & Valley, and parts of Piedmont especially in the vicinity of the Watchung and Palisades ridges.
G1. **Extremely Coarse Granular Soil**	Includes coarse granular soil with significant cobble- and boulder-sized pieces. Must contain 50% or more particles classified as cobble-size or larger (>75 mm diam.).	Highlands, Ridge & Valley, and parts of Piedmont, especially in the vicinity of the Watchung and Palisades ridges.
R1. **Weak Rock**	Includes all bedrock types not meeting the requirements of 'Sound Rock' R0 above. Such rock typically exhibits higher fracture frequency, more intense weathering, lower strength, or a combination of these. Classification of weak rock can usually be made on the basis of recover ratio, RQD and degree of weathering (visual inspection). Optionally, measure the Slake Durability Index (SDI)[3] of extracted cores or block samples, which will range from 80-90 for weak rock. Materials with an SDI of less than 80 should be treated as soil.	Mostly in Southern Piedmont; occasional in Highlands and Ridge & Valley
Moderate Erosion Resistance		
G2. **Coarse Granular Soil**	Includes well graded gravels, sandy gravels, clayey gravels, and silty gravels with an average minimum D_{50} of 40 mm and uniformity coefficient of 4 or more. Included are soils with Unified Classification of GW, GC, and GM.	Highlands, Ridge & Valley, and Piedmont
C2. **Hard Cohesive Soil**	Includes hard, cohesive soils such as clay, silty clay, sandy clay, and boulder clay exhibiting an average minimum unconfined compressive strength of 1.5 tons/ft^2 or greater. Included are soils with Unified Classification of CL, CH, MH, SC, and GC.	Mostly in Northern and Western Coastal Plain; occasional in Piedmont and Ridge & Valley provinces.
Low Erosion Resistance		
G3. **Fine to Medium Granular Soil**	Includes cohesionless, granular soils such as sand, silt, and gravel, and mixtures of these soils that do not meet the requirements of 'Coarse Granular Soil' G2 above. Included are soils with Unified Classifications of SW, SP, SM, GW, GP, GM, GC, ML, and MH.	Dominates in Coastal Plain; can occur in larger valleys of other provinces.
C3. **Soft Cohesive Soil**	Includes soft, cohesive soils such as clay, silty clay, clayey silt, plastic silt, and organic silts and clays. Soils in this classification will exhibit an average unconfined compressive strength of less than 1.5 tons/ft^2. Included are soils with Unified Classifications of CL, CH, MH, OL, and OH.	Parts of Piedmont, especially glacial lakes; occurs infrequently in other provinces.

Table 4 – Definition of SEM Erosion Classes (continued)

Notes:

1 - Particle size ranges are in accordance with the Unified Classification System as described in ASTM D2487:

Clay: < 0.002 mm	Gravel: > 6.35 mm and < 75 mm
Silt: > 0.002 mm and < 0.075 mm	Cobbles: > 75 mm and < 254 mm
Sand: > 0.075 mm and < 6.35 mm	Boulders: > 254 mm

2 – RQD is the abbreviation for “Rock Quality Designation” and is described in ASTM D6032.

3 – Measurement of the Slake Durability Index is described in ASTM D4644.

Erosion of this bed material over the engineering life of the structure is not significant. A complete definition of this material is given in **Table 4**.

> ***Scour for existing bridges.*** When evaluating potential scour depths of existing bridges founded on sound rock, the maximum scour depth shall not exceed the top of rock elevation. The geotechnical risk for bridges founded on sound rock (class R0) is low. Consult Module 1 of the Scour Evaluation Model**.**
>
> ***Scour for new bridges.*** The design scour depth for new bridge foundations placed on sound bedrock shall be assumed to coincide with the top of rock elevation. Spread foundations may be placed directly on a prepared rock surface that is free of soil or surface weathering. Blasting is not permitted for rock excavation for footings. Footings may be optionally keyed into the rock, and if so, sliding stability will be considered as satisfied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

G1. Extremely Coarse Granular Soil: This class includes coarse granular soil with a dominance of cobble- and boulder-sized particles. A complete description of this material is given in **Table 4**. These geologic materials are extremely coarse and highly erosion resistant. They are principally derived from glaciofluvial valley trains, reworked boulder tills, and stony colluvium in the northern part of the state. This erosion class typically develops significant natural armoring as the finer particles are winnowed out during high flow events. These deposits also share a common characteristic of increasing coarseness with depth. Recognition of this “hard bed” classification is among the unique features of the Scour Evaluation Model.

> ***Scour for existing bridges.*** The geotechnical risk for bridges founded on extremely coarse granular soil (class G1) is typically low. An important first step in scour analysis for these materials is to estimate the grain size distribution. Standard sampling methods and sieve analyses are not useful given the huge size of the sediments. Suggestions for field analysis of these extremely coarse materials are included in **Appendix B4**.
>
> Foundation stability for G1 class beds is determined using assessed or calculated scour conditions. The calculation methods described here are one of several available tools, and engineering judgment should be applied in making scour evaluations. Selected HEC-18 methods may be applicable for G1 sediments as described below.

Abutments: For abutments in coarse granular soil, the NCHRP 24-20 method for total scour (Ettema et al, 2011) is available. However, only the clear-water version is considered applicable to G1 sediments given their extreme coarseness. The relation appears as Eq. 8.6 in the 5th edition of HEC-18 and, for convenience, is in **Appendix A**. Note that the assumption of clear-water conditions is reasonable due to the large particle size of this erosion class and the typically low contraction ratios for New Jersey bridges. The NCHRP 24-20 method stipulates clear-water as long as the length of embankment is less that 75 percent of the floodplain width. It is further noted that the 24-20 relationship estimates total scour, so a separate calculation for contraction scour is not required.

Piers: Pier scour may be estimated using the coarse-particle equation developed by FHWA using USGS field data (FHWA 2012). The FHWA equation appears as Eq. 7.34 in the 5th edition of HEC-18 and is in **Appendix A** for convenience. Note that this equation is only applicable to clear-water flow conditions and to coarse-bed materials with $D_{50} > 20$ mm and $\sigma \geq 1.5$.

Note that to estimate total scour in the vicinity of a pier, the effect of contraction scour should also be added to the local scour computed above. Clear water conditions can normally be presumed for G1 sediments given their extreme coarseness. Therefore, Eqs. 6.4 and 6.5 in HEC-18, 5th edition may be used to estimate the effects of contraction scour, if any, in the vicinity of the pier. Note that the computed contraction scour for this erosion class may be low or even zero, again, on account of the extreme coarseness.

Once scour depth is estimated for the piers and/or abutments, it is compared with the actual depth of embedment of the foundations into the stream bed. Consult Module 1 of the Scour Evaluation Model.

Scour for new bridges. For new bridges built on extremely coarse granular soil, follow the procedures described above for 'existing bridges' to estimate depth of scour. Drilled pier foundations should also be considered for support.

Backfilling of all stream-side excavated areas shall be made with durable riprap sized in accordance with HEC-23 unless other scour countermeasures are designed and applied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

R1. Weak Rock: This class shall include all bedrock types not meeting the requirements of 'Sound Bedrock' as described in classification R0. Weak rock typically exhibits a higher fracture frequency, more weathering, lower strength, or a combination of these. Nevertheless, the amount of erosion observed at bridges founded on weak rock is normally minor. A complete description of this material is given in **Table 4**.

Rock that is in an advanced state of weathering may not meet the criteria for weak rock, i.e. low recovery, RQD, and/or SDI. Such material is usually referred to as saprolite and should be analyzed as soil. Selection of the appropriate erosion class depends on its physical nature. If the weathering products are predominantly cohesive, then analyze the material as erosion class C2. Alternatively, if the material is mostly friable and granular, then use class G2 or G3. Geotechnical tests may be needed to confirm the erosion class.

In New Jersey, most situations involving bridges on R1 beds will occur in the Piedmont province. Here the predominant bedrock is the Passaic Formation, formerly known as the Brunswick Formation. It consists mostly of alternating beds of red-brown mudstone, shale, and sandstone. Although the rock is moderately sound at many locations and may classify as Sound Rock R0, it can also be weaker and/or weathered near the surface, in which case it would classify as R1. The latter condition is more common in the southern, non-glaciated section of the Piedmont.

Scour for existing bridges. The geotechnical risk for bridges founded on R1 class rock is usually low. An important first step in scour analysis for bridges founded on R1 beds is to verify the classification using the guidance provided in **Table 4**.

Foundation stability for R1 beds is determined using assessed or calculated scour conditions. The calculation methods described here are one of several available tools, and engineering judgment should be applied in making scour evaluations.

Abutments: None of the HEC-18 relations have shown adequate correlation for scour evaluation of abutments in R1 class beds, so the following empirical depth method is recommended. Determine and compare the elevations of the top of rock with the elevations of the foundation footings. If the footing bottom on average is at least 1 foot below the rock surface, the geotechnical risk is considered low.

Piers: The pier scour equation for erodible rock by Annandale (2006) in the 5th edition of HEC-18 may be appropriate for weak rocks that occur in New Jersey. This relationship correlates scour depth with a parameter known as the erodibility index, K, which depends on a number of rock mass properties including intact strength, as well as joint spacing, condition, and orientation. The method further assumes that the predominant scour mechanism will be quarrying and plucking rather that abrasion. The equation for erodibility index appears as Eq. 7.37 in HEC-18, 5th ed. and, for convenience, is in **Appendix A.**

In practice, erodibility index K is reported to range rather widely from 0.1 (very poor rock) to 10,000 (very good rock). However, some of the input properties required to compute the index are difficult to measure directly from drill cores and thus are usually “guessed.” Since most cases of scour in R1 beds will occur in the Passaic mudstones and shales located in the Piedmont, the following values of K are provided:

K for R1 rock of Passaic Formation: Probable Range = 15 to 40+
Typical Average = 25

Once the value of K has been estimated, the scour depth y_s is computed using HEC-18 Eqs. 7.38, 7.39, and 7.40. These relationships are in **Appendix A** for convenience.

As a final step, the actual depth of embedment of the pier foundations beneath the rock surface is compared with the values above. Note that in situations where sediments overlie the R1 beds, a stratified analysis approach should be used as described in report section “Compound and Stratified Erosion Classes” on page 44. Consult Module 1 of the Scour Evaluation Model.

Scour for new bridges. For new bridges built on R1 beds, drilled pier foundations are the preferred method of support. The scour depth for design purposes may be estimated following the procedures described above for existing bridges.

Blasting is not permitted for rock excavation for footings. Backfilling of all stream-side excavated areas shall be made with durable riprap sized in accordance with HEC-23 unless other scour countermeasures are designed and applied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

Geological Materials with Moderate Erosion Resistance

Geologic materials in this classification exhibit a moderate resistance to erosion by scour action. Included are coarse, granular soil and hard, cohesive soil. The scour behavior of such materials is generally controlled by cumulative flow over time.

G2. Coarse Granular Soil: This classification shall include gravels, sandy gravels, clayey gravels, and silty gravels with an average minimum D_{50} of 40 mm and a uniformity coefficient of 4 or greater. Included are soils with Unified Classifications of GW, GC, and GM. These soils exhibit moderate erosion resistance due to their coarse particle size and well graded distribution, as well as a tendency to develop some natural armoring. Such geologic materials may be encountered throughout the Piedmont, Highlands, and Ridge & Valley provinces.

Scour for existing bridges. The geotechnical risk for bridges founded on coarse granular soil (class G2) ranges from medium to high depending on bridge age and evidence of substantial field scour. Consult Module 1 of the Scour Evaluation Model.

Foundation stability for G2 class beds is determined using assessed or calculated scour conditions. The calculation methods described here are one of several available tools, and engineering judgment should be applied in making scour evaluations. For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, it is recommended that scour depth be estimated using envelope curves, supplemented with HEC-18 methods, as appropriate. In the other provinces, the use of HEC-18 methods may be applicable. See Module 2 of the Scour Evaluation Model.

Abutments: For abutments in granular soil, the NCHRP 24-20 method for total scour (Ettema et al, 2011) is available. Both clear-water and live-bed equations are provided in this method. Thus, it is first necessary to determine whether live-bed or clear-water conditions are present. This requires a comparison of the critical velocity based on median size particles (D_{50}) with the design storm velocity using HEC-18 Eq. 6.1. Live-bed scour occurs if storm velocity is greater than the calculated critical velocity. If live-bed conditions exist, then use HEC-18 Eqs. 8.3 through 8.5 to estimate scour depth. If clear-water, then apply HEC-18 Eqs. 8.3, 8.4, and 8.6. Note that the 24-20 relationship estimates total scour, so a separate calculation for contraction scour is not required. For convenience, all applicable relationships are in **Appendix A**.

Piers: Two pier scour equations are available in the 5th edition of HEC-18 for G2 size sediments. The first is the coarse-particle equation developed by FHWA based on USGS field data (FHWA 2012). The FHWA equation appears as Eq. 7.34 in the 5th edition and, for convenience, is in **Appendix A**. Note that this equation is only applicable to clear-water flow conditions and to coarse-bed materials with $D_{50} > 20$ mm and $\sigma \geq 1.5$. Otherwise, HEC-18 Eq. 7.1 may be used to estimate scour depth. It is known as the "HEC-18 Equation" and is derived from the Colorado State University (CSU) equation.

Note that to estimate total scour in the vicinity of a pier, the effect of contraction scour should also be added to the local scour computed above. For live bed conditions, use HEC-18 Eqs. 6.2 and 6.3 in conjunction with the HEC-18 Equation if applicable. For clear water conditions, use Eqs 6.4 and 6.5 in conjunction with the coarse-particle equation, as applicable. For convenience, all relationships are in **Appendix A**.

Scour for new bridges. New bridges built on coarse granular soil shall be supported on deep foundations. For all new bridges, it is recommended that scour depth for design purposes be estimated using HEC-18, 5th ed. procedures described above for 'existing bridges.' For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, envelope curves may be used as a "verification check" to the primary method of analysis.

Backfilling of all stream-side excavated areas shall be made with durable riprap sized in accordance with HEC-23 unless other scour countermeasures are designed and applied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

C2. Hard Cohesive Soil: This classification shall include clay, silty clay, sandy clay, and boulder clay that has an average minimum unconfined compressive strength of 1.5 tons/ft^2 or greater. Included are soils with Unified Classifications of CL, CH, MH, SC and GC. These soils exhibit moderate erosion resistance due to their high cohesive strength. Such geologic material is characteristic of the Cretaceous clays of the Inner Coastal Plain province, and may also be encountered occasionally in portions of the Piedmont and Ridge and Valley Provinces.

The scour mechanism and erosion rate for cohesive soil is quite different than for granular soils. Granular soil can erode in a matter of hours when subjected to highly elevated flow velocities and eddy currents. In contrast, cohesive soils erode more gradually over time owing to the inter-particle bonding of clay minerals. So, in cohesive soils, total scour directly depends on the *cumulative hydraulic power* that a streambed experiences over its lifetime in excess of the clay's critical shear stress.

As a consequence of this physiochemical difference, the predictive tools for scour estimation in cohesive soils are not as well developed. The 5th edition of HEC-18 provides tentative methods for estimating scour in cohesive soils, including the ultimate contraction scour equation (HEC-18, Eq. 6.6), the time rate of scour equation (HEC-18, Eq. 6.8), and the pier scour equation (HEC-18, Eq. 7.35). These are all based on the Scour Rate In Cohesive Soil (SRICOS) method developed by Texas A&M University. Collectively, these relationships require some parameters that are difficult to obtain with an acceptable level of accuracy, such as the initial rate of scour, critical shear stress to induce scour, and a bridge-life flow hydrograph. An additional complication is that specialized laboratory testing equipment and techniques are required to obtain some values, such as the SRICOS- Erosion Function Apparatus (SRICOS-EFA). As a result, only the ultimate contraction scour equation is included in these scour guidelines. Practitioners interested in applying other HEC-18 cohesive relations are referred to Briaud et al 2003, Briaud et al 2009, and Briaud et al 2011, which fully describe the SRICOS method.

The number of bridges in New Jersey with bed sediments consisting solely of undisturbed cohesive soil is not large. This is mostly due to the geomorphology and geologic history of the State's river systems. Even bridge sites underlain by native clay will typically have a streambed consisting of recent silts, sands, and gravels that overlie the clay, having been deposited since the retreat of the Wisconsin ice sheet. The veneer of largely non-cohesive sediments, when present, can often be analyzed using envelope curves or HEC-18 procedures for erosion classes G1, G2, or G3. However, when the sediments in the scourable zone do consist of class C2 sediments, the following guidance is offered.

> ***Scour for existing bridges.*** The geotechnical risk for bridges founded on hard cohesive soil (class C2) ranges from medium to high depending on bridge age and evidence of field scour. Consult Module 1 of the Scour Evaluation Model.
>
> Foundation stability for C2 class beds is determined using assessed or calculated scour conditions. The calculation methods described here are one of several available tools, and engineering judgment should be applied in making scour evaluations. For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, it is recommended that scour depth be estimated using envelope curves, supplemented with the HEC-18 methods, as appropriate. In the other provinces, the use of HEC-18 methods may be applicable. See Module 2 of the Scour Evaluation Model.
>
> Contraction Scour: The ultimate scour equation, HEC-18, Eq. 6.6, is available to estimate contraction scour over the life of a bridge in cohesive soil. Note that ultimate scour may never be reached during the life of a bridge if there is not sufficient duration of high flow, but the relation does provide a "worst case" estimation. The key geotechnical variable in the equation is τ_c, the critical shear stress required to detach and mobilize the sediment particles. The value of τ_c can be determined by laboratory testing or selected from HEC-18, Fig. 6.11. The table below, which provides typical ranges of critical shear stress for C2 and C3 sediments, may also be used.

Typical Values of Critical Shear Stress

SEM Erosion Class	Typical Range of Critical Shear Stress, τ_c
C2, Hard Cohesive Soil	0.1 to 0.8 lb/ft^2
C3, Soft Cohesive Soil	0.02 to 0.2 lb/ft^2

For new designs or recently constructed bridges, it may be appropriate to use the full value of ultimate contraction scour. For existing bridges, especially those 50 years or older, it is reasonable to use a fraction of the ultimate value to predict the remaining future scour. A comparison of current streambed elevations with original as built elevations is useful for this analysis, if available. One approach for estimating future scour is by proportion, that is, multiply ultimate scour by the ratio of remaining bridge life to total bridge life. Sound engineering judgment should be applied in making contraction scour estimates.

Abutment Scour: The estimation of local abutment and pier scour for cohesive soils is more difficult since, as mentioned previously, the new relationships in HEC-18, 5th ed. require some geotechnical and hydrologic parameters that are difficult to obtain. As a consequence, the practitioner may choose to give more reliance to envelope curves in estimating scour for abutments, when they are applicable. Other HEC-18 relationships may also be adapted for abutments, including the classic Froehlich (HEC-18, Eq. 8.1) and HIRE (HEC-18, Eq. 8.2) equations, which still appear in the 5th edition. The NCHRP 24-20 method for total scour (Ettema et al, 2011) is also available. For cohesive soils, use the clear-water version, HEC-18 Eq. 8.6 (Note that the 24-20 relationship estimates total scour, so a separate calculation for contraction scour is not required). The applicability of the Froehlich/HIRE equations and the 24-20 relationship to cohesive soils is limited, however, since the former does not consider particle size and the latter assumes non-cohesive sediment with a particle diameter greater ≥ 0.2 mm. So, these HEC-18 relationships may yield unrealistically high abutment scour values when applied to cohesive soil. Sound engineering judgment should be applied in making scour estimates for abutments in cohesive soil.

Pier Scour: Two approaches to estimate the depth of local scour may be used for piers founded in erosion class C2 sediments. The first is the “HEC-18 Equation,” which is derived from the Colorado State University (CSU) equation. This relation has demonstrated generally good correlation with field scour observations throughout the U.S., and it appears as Eq. 7.1 in the 5th edition of HEC-18. Note that the HEC-18 Equation does not consider particle size or cohesion and would, consequently, tend to give conservative results. The second approach is to use a “limiting ratio” of scour depth to pier width, or y_s/a. For round nose piers, HEC 18, 5th ed. recommends a maximum ratio value of 2.4 for Froude Numbers less than or equal to 0.8 and 3.0 for larger Froude Numbers. These provide yet another estimate of local scour (See HEC-18, Section 7.1, and Eq. 7.2). Note that to estimate total scour in the vicinity of a pier, the effect of contraction scour should also be added to the local scour computed above. Sound engineering judgment should be applied in making scour estimates for piers in cohesive soil.

Scour for new bridges. All new bridges built over hard cohesive soils shall be supported on deep foundations. For new bridges, it is recommended that scour depth for design purposes be estimated using the procedures described above for 'existing bridges.' For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, envelope curves may be used as a "verification check" to the primary method of analysis.

Backfilling of all stream-side excavated areas shall be made with durable riprap sized in accordance with HEC-23 unless other scour countermeasures are designed and applied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

Geological Materials with Low Erosion Resistance

Certain kinds of geological materials possess low resistance to erosion and may exhibit significant scour during high stream flows. These include granular soils with fine to medium textures and soft cohesive soils.

G3. Fine to Medium Granular Soil: This classification shall include cohesionless granular soils such as sand, silt and gravel, and mixtures of these soils that do not meet the requirements of 'Coarse Granular Soil' as described in class G2. Included are soils with Unified Classifications of SW, SP, SM, GW, GP, GM, GC, ML, and MH. This kind of soil dominates streambeds throughout the Coastal Plain province. It may also be encountered within the larger valleys of the other provinces, where stream gradients are mild.

Scour risk for existing bridges. The geotechnical risk for bridges founded on fine to medium granular soil (class G3) ranges from medium to high depending on bridge age and evidence of field scour. Consult Module 1 of the Scour Evaluation Model**.**

Foundation stability for G3 class beds is determined using assessed or calculated scour conditions. The calculation methods described here are one of several available tools, and engineering judgment should be applied in making scour evaluations. For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, it is recommended that scour depth be estimated using envelope curves, supplemented with the HEC-18 methods, as appropriate. In the other provinces, the use of HEC-18 methods may be applicable. See Module 2 of the Scour Evaluation Model.

Abutments: For abutments in granular soil, the NCHRP 24-20 method for total scour (Ettema et al, 2011) is available. Both clear-water and live-bed equations are provided in this method. Thus, it is first necessary to determine whether live-bed or clear-water conditions are present. This requires a comparison of the critical velocity based on median size particles (D_{50}) with the design storm velocity using Eq. 6.1 in the 5th edition. If live-bed conditions are found to exist, then use HEC 18 Eqs. 8.3 through 8.5 to estimate scour depth. If clear-water, then apply HEC-18 Eq. 8.6. Note that the 24-20 relationship estimates total scour, so a separate calculation for contraction scour is not required. For convenience, the relationships are in **Appendix A**.

Piers: For piers founded in granular soil, the "HEC-18 Equation" is available to estimate scour depth. It is derived from the Colorado State University (CSU) equation, which has demonstrated generally good correlation with field scour observations throughout the U.S. This relation appears as Eq. 7.1 in the 5th edition of HEC-18. Note that to estimate total scour in the vicinity of a pier, the effect of contraction scour should also be added to the local scour computed above. For live bed conditions, use HEC-18 Eqs. 6.2 and 6.3 in conjunction with the 'HEC-18 Equation' if applicable. For clear water conditions, use Eqs 6.4 and 6.5. For convenience, the relationships are in **Appendix A**.

Scour for new bridges. New bridges built on fine to medium granular soil shall be supported on deep foundations. For all new bridges, it is recommended that scour depth for design purposes be estimated using HEC-18, 5th ed. procedures described above for 'existing bridges.' For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, envelope curves may be used as a "verification check" to the primary method of analysis.

Backfilling of all stream-side excavated areas shall be made with durable riprap sized in accordance with HEC-23 unless other scour countermeasures are designed and applied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

C3. Soft Cohesive Soil: This classification shall include soils possessing various amounts of cohesion including clay, silty clay, clayey silt, plastic silt, and organic silts and clays. Soils in this classification will exhibit an average unconfined compressive strength of less than 1.5 tons/ft^2. Included are soils with Unified Classifications of CL, CH, MH, OL, and OH. This kind of soil can occur in parts of the Piedmont, especially glacial lakes. Soft, cohesive soil also occurs infrequently in streambeds of the other provinces.

The scour mechanism and erosion rate for cohesive soil is quite different than for granular soils. A narrative describing the general scour behavior of cohesive soils was previously provided in report section, "Geological Materials with Moderate Erosion Resistance" (C2, Hard Cohesive Soil) on page 39." These same general concepts apply to sediments in erosion class C3, Soft Cohesive Soil.

Scour for existing bridges. The geotechnical risk for bridges founded on soft, cohesive soil (class C3) ranges from medium to high depending on bridge age and evidence of field scour. Consult Module 1 of the Scour Evaluation Model.

Foundation stability for C3 class beds is determined using assessed or calculated scour conditions. The calculation methods described here are one of several available tools, and engineering judgment should be applied in making scour evaluations. For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, it is recommended that scour depth be estimated using envelope curves, supplemented with HEC-18 methods, as appropriate. In the other provinces, HEC-18 methods may be applicable. See Module 2 of the Scour Evaluation Model.

Selected methods in HEC-18, 5th ed. to estimate scour depth in cohesive soil were previously described in report section, “Geological Materials with Moderate Erosion Resistance” (C2, Hard Cohesive Soil) on page 39. The primary difference in applying these equations to C3 Sediments is in the critical values that should be used, such as critical shear and critical velocity. Note that C3 sediments will tend to scour more quickly and deeper over time than C2 sediments and that, as always, sound engineering judgment should be applied when making scour estimates in these erosion classes.

Scour for new bridges. All new bridges built on soft cohesive soils shall be supported on deep foundations. For new bridges, it is recommended that scour depth for design purposes be estimated using the procedures described above for ‘existing bridges.’ For bridges located in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, envelope curves may be used as a “verification check” to the primary method of analysis.

Backfilling of all stream-side excavated areas shall be made with riprap sized in accordance with HEC-23 unless other scour countermeasures are designed and applied. All other requirements outlined in Section 39 of the NJDOT Design Manual for Bridges and Structures and related standards shall be followed.

Compound and Stratified Erosion Classes

In some situations, a bridge may be founded on streambed materials that fall into two or more erosion classes. It is recommended that sound engineering judgment be applied in such cases, while taking the following factors into consideration.

If the variation in soil and rock types is mostly horizontal in that one erosion class grades into another, the preferred approach is to use the “predominant” erosion class. Keep in mind that bed sediments in the vicinity of the upstream fascia are generally the most susceptible to scour action. A second approach is to analyze each erosion class individually, compare the results, and then choose one for the risk rating. The most conservative approach is to assume the geological material with the lowest resistance to erosion, i.e. the highest scour risk.

Situations may also be encountered where the streambed materials are stratified, i.e. there is vertical variation in the soil or rock types. If the variation is sufficient to warrant classification into two or more different erosion classes, the following approach is recommended. Analyze the surficial layer first using the appropriate erosion class and the hydraulic parameters of the original channel. If scour depth is found to be less than the total thickness of the layer, then use that scour value. However, if the estimated scour depth is found to penetrate the entire first layer, then perform a second scour analysis on the next lower layer. Make sure to use the erosion class of the second layer and the hydraulic parameters of the deepened channel, i.e. assume the surficial layer is removed. If the estimated scour depth also exceeds the second layer, then repeat the process again using the erosion class and hydraulic parameters for each successive layer until the scour depth in a layer is less than the total thickness of that layer. The total scour is then the sum of the scour values determined for each individual layer.

Long-term Channel Stability

An important part of scour analysis is to assess the long-term stability of the stream channel in the vicinity of the bridge. This is because channels exhibiting evidence of instability are more likely to have scour problems around the foundations. While a number of factors influence channel stability, the erosion resistance of the bed and bank materials are quite important. So, streams flowing through geologic materials with lower erosion resistance such as classes G2, G3, C2, and C3 are more likely to develop channel instability. Conversely, streams flowing through geologic materials with high erosion resistance such as classes R0, R1, and G1 are not that susceptible.

Assessment of channel stability is best performed using a combination of field inspection and desk study. The first step is to classify the channel form or pattern. The most basic river classification system uses three channel patterns: straight, meandering, or braided. "Straight" channels have roughly parallel banks that are linear or gently curving. A "meandering" river consists of two consecutive loops, one flowing clockwise and the other counter-clockwise. A meandering channel is usually actively eroding one bank and depositing sediments on the other. This channel pattern is normally associated with relatively flat channel slope and terrain. A stream is considered "braided" when its flow is divided at normal stage by small mid-channel bars or small islands. Braiding indicates that the stream is burdened with excess sediment and is often associated with active aggradation or degradation of the channel. When assessing channel patterns, the observer should walk at least 10 channel widths upstream and downstream of the bridge. Aerial photos of the surrounding area should also be viewed.

The presence and extent of degradation or aggradation should also be investigated. "Degradation" refers to a long-term lowering of the channel over a relatively wide area, while "aggradation" is the progressive buildup of sediments in the channel. Degradation can sometimes be identified by the presence of a stain or other marking along piers or abutment walls that indicate a previous bed elevation. Aggradation can be identified by the presence of bars or other elevated portions of the streambed, possibly comprised of materials inconsistent with those in the rest of the channel. Long term degradation/aggradation can be assessed by examining as-built drawings, Stage II studies, and past bridge inspection reports and fascia soundings. Examine and compare historic cross sections and longitudinal profiles to identify trends. This helps to establish the current amount of sediment cover over the foundations.

There are a number other channel stability indicators that are useful in assessing river channels. HEC-20, 4th ed. (Lagasse et al, 2012) provides 13 key indicators of channel stability that were determined from the literature and field observations. These are:

1. Watershed and floodplain activity and characteristics
2. Flow habit
3. Channel pattern
4. Entrenchment/channel confinement
5. Bed material
6. Bar development
7. Obstructions, including bedrock outcrops, armor layer, large woody debris jams, grade control, bridge bed paving, revetments, dikes or vanes, riprap
8. Bank soil texture and coherence
9. Average bank slope angle
10. Vegetative or engineered bank protection
11. Bank cutting
12. Mass wasting or bank failure
13. Upstream distance to bridge from meander impact point and alignment

Most of these indicators are routinely evaluated as part of the Scour Evaluation Model (SEM) during the Field Scour Investigation (see report section “Step 2- Field Scour Investigation” on page 48). An inspection form and accompanying narrative to facilitate field investigation are also provided (See **Appendices 2C** and **2D**). When more in-depth analysis of channel stability is desired, FHWA’s “Rapid Assessment Method” for channel stability may be consulted. The method generates a numerical rating for all 13 of the indicators listed above, which are then summed for a total channel score (see HEC-20, Section 5.4.2).

Geotechnical Evaluation Procedure Steps

There are four steps in evaluating the scour susceptibility of geologic materials that surround and support bridge substructures. They are described as follows:

Step 1- Geotechnical Reconnaissance Study

A thorough desk study of available geologic information sources shall be conducted for every bridge site. It shall investigate the nature of the alluvium delineated within the stream channel itself. It shall also focus on the soil/rock units that underlie and adjoin the site. This is because: (1) the very same formations typically underlie the alluvium, often at relatively shallow depth; and (2) the bed materials themselves are principally derived from the surrounding geologic formations. In addition, any unique formations or deposits located some distance upstream or downstream of the bridge shall also be investigated, as these can also impact the subsurface conditions at a bridge. For example, the presence of a lacustrine fan downstream may indicate that soft clay underlies the alluvium at the bridge site, while a hard rock colluvium located upstream may suggest that cobbles and boulders are present in the channel at shallow depth.

The reconnaissance investigation should also examine other pertinent data such as the Stage II Study and NBIS inspection reports. In summary, the following is a list of publications and other information that should be consulted during this office study phase:

- Surficial and Bedrock Geology Maps, New Jersey Geological Survey (USGS, 1996, 1998, 2002, 2000)
- Engineering Soil Surveys of New Jersey, Rutgers University (by county) (Rutgers, 1951)
- Web Soil Survey, U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (by county) (USDA)
- Soil Boring Logs, NJDOT Geotechnical Database Management System (NJDOT)
- Geotechnical Investigation Report for original bridge construction (for existing bridges, if available)
- Stage II Scour Evaluation Study (for existing bridges if available) (Stage II Reports)
- NBIS Inspection Results (on file with NJDOT)

During the reconnaissance investigation, it is important to determine the elevation of existing footings or pile caps in relation to the original stream bed elevation. Such data can be extracted from Stage I and Stage II studies or as-built files. Additionally, changes in the stream bed elevation since construction should also be examined to determine: (1) current amount of cover over the foundations; and (2) long-term aggradation or degradation of the channel. These data are typically available in NBIS bridge inspection reports in the form of fascia soundings. Ultimately, knowledge of the relative elevations of the foundation and stream bed is necessary for making decisions in the Scour Evaluation Model (SEM).

Caution should be exercised when extracting geotechnical data from the Stage II studies for scour critical bridges. A detailed review of over 30 reports showed that many contained methodology errors in the analysis of stream bed sediments. For example, most investigations used surface “grab” sampling or hand augering. These sampling techniques typically penetrate only several inches or, at most, a few feet into the streambed, and they do not establish a representative geologic profile. A related problem was improper sample collection. Sometimes, only fine sediments were recovered for laboratory analysis, while the oversize gravel, cobbles, and boulders were ignored. Irregularities in interpretation of the sieve analysis curves were also noted. The net result of these errors was a compound bias towards finer grain sizes, resulting in an inaccurate geologic profile and computed scour values that were overly conservative.

<u>Reporting Requirements</u>: If the bridge is a new design, then the results of the reconnaissance study are normally incorporated into the structure’s “Geotechnical Investigation Report.” If the scour evaluation is being conducted for an existing bridge, the results of the office and field phases shall be summarized in a separate “Geotechnical Reconnaissance Study.” Example reconnaissance studies for selected scour critical bridges are included in **Appendix C** of this research report.

Step 2- Field Scour Investigation

Upon completion of the reconnaissance analysis, a field investigation of the bridge shall be made to evaluate the scour risk. One principal objective of the field visit is to assess the erosion class of the streambed materials. Another principal objective is to check for evidence of scour holes, erosion zones, degradation, and aggradation. Observations will be made for each substructure unit. It is also important to determine how consistent the results of the reconnaissance analysis are with actual field observations. In addition to characterizing the streambed, a record shall be made of debris presence, debris potential, bank erosion, skew, bed slope, and condition of existing countermeasures, if present.

A standard field inspection form was developed for NJDOT to record the observations during the field investigations. The form prompts the user to carefully evaluate the characteristics of the stream bed that can affect scour risk. The field inspection form is provided in **Appendix B3**, and a narrative describing procedures for conducting a field inspection is presented in **Appendix B4**. Other guides for conducting scour field inspections are also available, e.g. Cinotto and White (2000), FHWA (2009) and Forest Service (1998).

Photography is a critical part of the Field Scour Investigation to document the existing condition of the bridge, especially the substructure and stream channel. Whenever possible, field visits should be conducted during low water conditions like during the summer and early fall, when the most foundation elements and channel features are typically exposed and visible. At a minimum, the following views should be recorded: (1) channel looking upstream; (2) upstream fascia; (3) substructures and channel under the bridge; (4) downstream fascia; and (5) channel looking downstream. In addition, all areas of exposed streambed, riprap, channel erosions, and scour zones should also be photographed.

Reporting Requirements: The results of the field investigation shall be reported in a "Field Scour Investigation Summary" that documents the following:

- Bridge Name and Number
- Construction Date(s)
- Bridge Structure Type
- Stream Bed Classification and Field Description
- General Channel Observations
- Scour observations
- Conclusions Related to Scour
- Other Findings
- Photos

Example field investigative studies for selected scour critical bridges are included in **Appendix C** of this research report.

Step 3 - Detailed Investigation (Optional)

In some cases it will not be possible to confirm the erosion class of stream bed at the conclusion of the reconnaissance and field investigation studies. In that event, an optional detailed subsurface investigation shall be conducted. In general, the subsurface investigation program shall be prepared in accordance the "Procedures for Consultants of the Bureau of Geotechnical Engineering."

Investigation of the streambed should focus on recovery of representative samples so that the erosion potential can be accurately assessed. Thus, consideration shall be given to supplementing the standard investigation program with the modified methods that yield data pertinent to scour evaluation. These are especially needed when evaluating geologic materials that are difficult to sample and test, including coarse granular soils with large gravel, cobbles, and boulders. Such modified methods include the use of an oversize split barrel (spoon) sampler and test pits excavated with a backhoe.

Step 4 - Determination of Erosion Class and Scour Risk

The fourth and final step of the geotechnical evaluation is the confirmation of the erosion class of the stream bed materials. Once the erosion class has been established, then an estimate of the scour risk and other design parameters can be made. The seven different erosion classes were defined previously in report section, "Description of Erosion Classes" on page 32. Each classification is defined using standard geotechnical indexes and tests, e.g. Unified System, ASTM Standards. Also included are notations about where the various erosion classes may be expected geographically within the State.

Once the erosion class is confirmed, then geotechnical scour risk is determined using Module 2 of the Scour Evaluation Model (SEM). This procedure is described in chapter, "NEW JERSEY SCOUR EVALUATION MODEL (SEM)" on page 61.

GUIDELINES - HYDROLOGIC/HYDRAULIC EVALUATION OF SCOUR RISK

Background

This chapter provides guidelines for evaluating hydrologic and hydraulic factors that affect the scour susceptibility of bridge substructures. An important objective of this research study is to standardize the methods used to conduct hydrologic and hydraulic analyses for scour evaluation of New Jersey bridges. A review of the Stage II studies revealed numerous inconsistencies in these analyses for the bridges on the scour critical list. As an example, stream discharges were developed using many different methodologies (e.g. extreme value, regression analysis), as well as data from different agencies (e.g. FEMA, USSCS, USGS). So, a new hydrologic/hydraulic reconnaissance analysis procedure is presented as a component of the Scour Evaluation Model (SEM).

An essential parameter in the hydrologic evaluation of a new or existing bridge to resist scour is the magnitude of the design flood. The 5th Edition of HEC-18 has upgraded the requirements for the scour design flood for new bridges from a 100 to a 200 year flow event (see discussion in report section, “HEC 18 Hydrologic and Hydraulic Requirements for Scour Evaluation” in chapter, “REVIEW - TRADITIONAL & ALTERNATE METHODS OF SCOUR ANALYSIS” on page 24).

Recent meteorological events provide additional motivation to improve the State’s scour evaluation procedures. In 2011 and 2012, New Jersey experienced two major storm events, Hurricane Irene and Tropical Storm Sandy – a tidal storm surge. Streams throughout the State have now experienced flows close to or in excess of 200 year events as a result of these storms. It is noteworthy that the only major bridge failure occurred in a tidal area (this research study does not address tidal area bridges). So, it is an opportune time to re-inspect the current inland scour critical bridges and reanalyze their scour susceptibility.

The previous chapter on geotechnical evaluation of scour risk demonstrated that portions of the State of New Jersey, particularly in the north, have stream beds with coarse soils that are more erosion resistant. However, the stream beds in the central and southern part of the State are dominated by fine grained soils and are, thus, more vulnerable to scour. These areas with fine grained soils comprise the Coastal Plain and Non-glaciated Piedmont/Highlands provinces.

Another objective of this research study is to develop an effective method to analyze the hydrologic and hydraulic risk of bridges located in the Coastal Plain and Non-glaciated Piedmont/Highlands provinces. In fact, there are 102 scour critical bridges within these two regions, representing more than 60% of bridges on the critical list. After a thorough review of available methods for analyzing scour depth, the Research Team concluded that the “envelope curve method” (Benedict and Conrad, 2006 and 2009) can be advantageously applied to bridges located in New Jersey’s the Coastal Plain and Non-glaciated Piedmont/Highlands provinces. The envelope curve procedure has been demonstrated by the USGS in comprehensive studies contracted with various state

DOT's in the U.S. over the past decade (e.g. South Carolina, Alabama, Maine). A USGS National Database of more general scour data from other states has also been used in that development (i.e. Alaska, Arkansas, Colorado, Georgia, Indiana, Louisiana, Ohio, Minnesota, Missouri, South Dakota, and Montana).

Envelope curves based upon actual measurements of scour depths in New Jersey have not been developed to date. However, the range of D_{50} values of the sediments from USGS studies conducted in the Coastal Plain and Piedmont regions of other states are very comparable to the D_{50} values from Stage II studies for these same regions within New Jersey. Thus, the Research Team has utilized envelope curves developed based on South Carolina data, as well as the National Bridge Scour Database, for scour evaluation of New Jersey bridges. The rationale for their use and the methodology for application will now be described.

Envelope Curves – Their Development and Applications to New Jersey

The general concept of the envelope curve is to define an upper range of observed scour depths for a given hydraulic variable that correlates best with the scour depth. So, the use of envelope curves is considered to be a conservative approach for assessing scour depths. In employing the concept, the USGS operates on the premise that measured scour depths represent a historical snapshot of conditions, and thus, need not be measured during actual storm events. Therefore, if an analyzed bridge has been in operation for a considerable number of years, the measured scour depths reflect its history. The average age of the bridges in the USGS studies ranged from 49 to 66 years, and, through the use of statistical analysis, it was postulated that these bridges encountered major storm events within a reasonable probability. Since the majority of bridges on the New Jersey Scour Critical List are 50 years or older, it can be argued that the same would be applicable in New Jersey.

Moreover, as part of this study, assessment of the return period associated with the largest stream flow actually recorded at each bridge and associated gage since the time of its construction were also conducted. As a consequence of Hurricane Irene and Sandy in 2011 and 2012, respectively, and resultant stream flow events across New Jersey, many streams have sustained a new flow of record.

The USGS studies derive envelope curves for both pier and abutment scour, as well as for contraction scour. The studies recognize the numerous variables associated with estimating scour depth (i.e. velocity, depth of flow, slope of riverbed, drainage area to the respective bridges, D_{50} soil grain size, and skew angle). However, the USGS isolates the variable that correlates most strongly with scour depth in all cases and then develops envelope curves connecting points of maximum measured scour depths across the range of the chosen key variable.

For assessment of local pier scour, the USGS envelope curves are based on a relationship between pier width and scour depth because the pier width correlates best with scour depth. In order to confirm this approach, the NJIT Research Team analyzed

384 USGS measured scour depths from 56 bridges in 14 states. These were compiled in a paper entitled “U.S. Geological Survey Field Measurements of Pier Scour” (Landers, Mueller and Richardson 1999). The statistical analysis demonstrated that scour depth had the strongest correlation with pier width in comparison with the other variables.

The South Carolina scour research related to envelope curve development indicates that the soil grain sizes within their Coastal Plains and Piedmont provinces are similar to New Jersey’s Coastal Plain and Non-glaciated Piedmont/Highlands provinces. The research further notes the similarity of soils between the National Bridge Scour Database (NBSD) and these same soil provinces in South Carolina for the purposes of generating envelope curves for pier scour.

Envelope Curves for Pier Scour: Envelope curves for pier scour generated both by South Carolina and utilization of the NBSD data are developed to relate scour depth (in feet) as a function pier width (in feet) based upon measured scour depths found in both the Coastal Plain and Non-glaciated Piedmont/Highlands provinces. That is, there is no differentiation of envelope curves handled separately for each soil province.

It should be noted that, in the South Carolina studies related to pier scour envelope curve development, the curve generated is applicable only to pier widths less than six (6) feet. For widths greater than six feet, Benedict and others suggest the applicability of the NBSD envelope curve for pier scour since the latter envelope curve performs well in comparison to the envelope curve based on South Carolina data for pier widths less than six feet.

Envelope Curves for Abutment Scour: For abutment scour, the USGS envelope curves and those developed by Benedict in South Carolina are based upon a direct relationship between embankment length blocking the flow and scour depth. Separate envelope curves are generated for the Coastal Plain and Non-glaciated Piedmont/Highlands provinces. These envelope curves were employed in the current study exactly as published without modification. And to be conservative, where more than one envelope curve was applicable to a specific soil province, the one providing the largest estimated scour depth at a particular pier width (for pier scour) or abutment length blocking flow (for abutment scour) was used in the analyses.

Envelope Curves for Pier Contraction Ratio and Abutments and Their Impacts on Total Scour Measurements: In the South Carolina studies, because actual scour patterns and locations were able to be readily observed and measured, the envelope curves developed for abutments represents the total scour (local scour and contraction scour).

For piers, the scour due to contraction may not necessarily occur at the same location as local scour. Therefore, separate envelope curves were developed for local pier scour (based on the pier widths) and for pier contraction scour (based on the contraction ratios), with the presumption that total scour is the sum of the two results.

However, Benedict, in attempting to develop envelope curves to estimate scour depths associated with pier contraction scour, indicates that “the results of this investigation do not identify a definitive method for assessing live bed contraction scour . . . .” Therefore, the current study determines total pier scour by first estimating local scour with envelope curves and then adding the value for contraction scour estimated with HEC-18 procedures.

For the current study, the NJIT Team performed an envelope curve analysis of 62 bridges located in the Coastal Plain and some 40 additional bridges in the Piedmont region. All the bridges had been previously determined to be scour critical as a result of the Stage II studies. The new envelope curve findings showed that a number of bridges had scour depths less than those calculated in the Stage II studies. In some cases, the differences are significant, with revised scour depths above existing pier and/or abutment footing elevations.

This research study recognizes that only a limited number of comprehensive USGS studies to date incorporate the envelope curve concept. Furthermore, these studies have been conducted in states other than New Jersey. As a result, the hydrologic/ hydraulic evaluation and risk analysis also relies on hydrologic investigations utilizing USGS gaged data and/or StreamStats data recently compiled by the USGS in New Jersey (Watson and Schopp, 2009). Each bridge is analyzed to see whether it has (or has not) experienced a 100-year flood event since the time of its construction. If so, this fact, in conjunction with the envelope curve findings, is used to prioritize those bridges in the Coastal Plain and Non-glaciated Piedmont/Highlands provinces.

Lastly, as an integral part of the hydrologic/hydraulic evaluation and envelope curve analysis, each bridge is visited by a team of experts (in hydrology, hydraulics, geotechnical, and structures) to examine the site in detail with the aid of photography. This identifies other potential vulnerabilities that might not be reflected in either envelope curve or hydrologic analyses. Note that the two cited storms, Irene and Sandy, have created a fortuitous opportunity to obtain real scour data associated with these rare flood events. Thus, a new Implementation Phase study is proposed to assess the impact on the stream beds and related infills for a number of scour critical bridges, including collection of data to create envelope curves specific to New Jersey’s Coastal Plain and Non-glaciated Piedmont/Highlands provinces.

A general schematic of the procedure followed to develop the envelope curves for New Jersey is shown in **Figure 5**. Details regarding the specific USGS studies investigated, including envelope curves are provided in **Appendices B1** and **B2. Table 5** shows a summary of the USGS envelope curve studies reviewed. Example Hydrologic/Hydraulic Analyses are contained in **Appendix C.**

Selection of Envelope Curves Appropriate to New Jersey

Following a review of the previously described studies, specific envelope curves were selected for scour analysis of New Jersey bridges. The selected curves were applicable

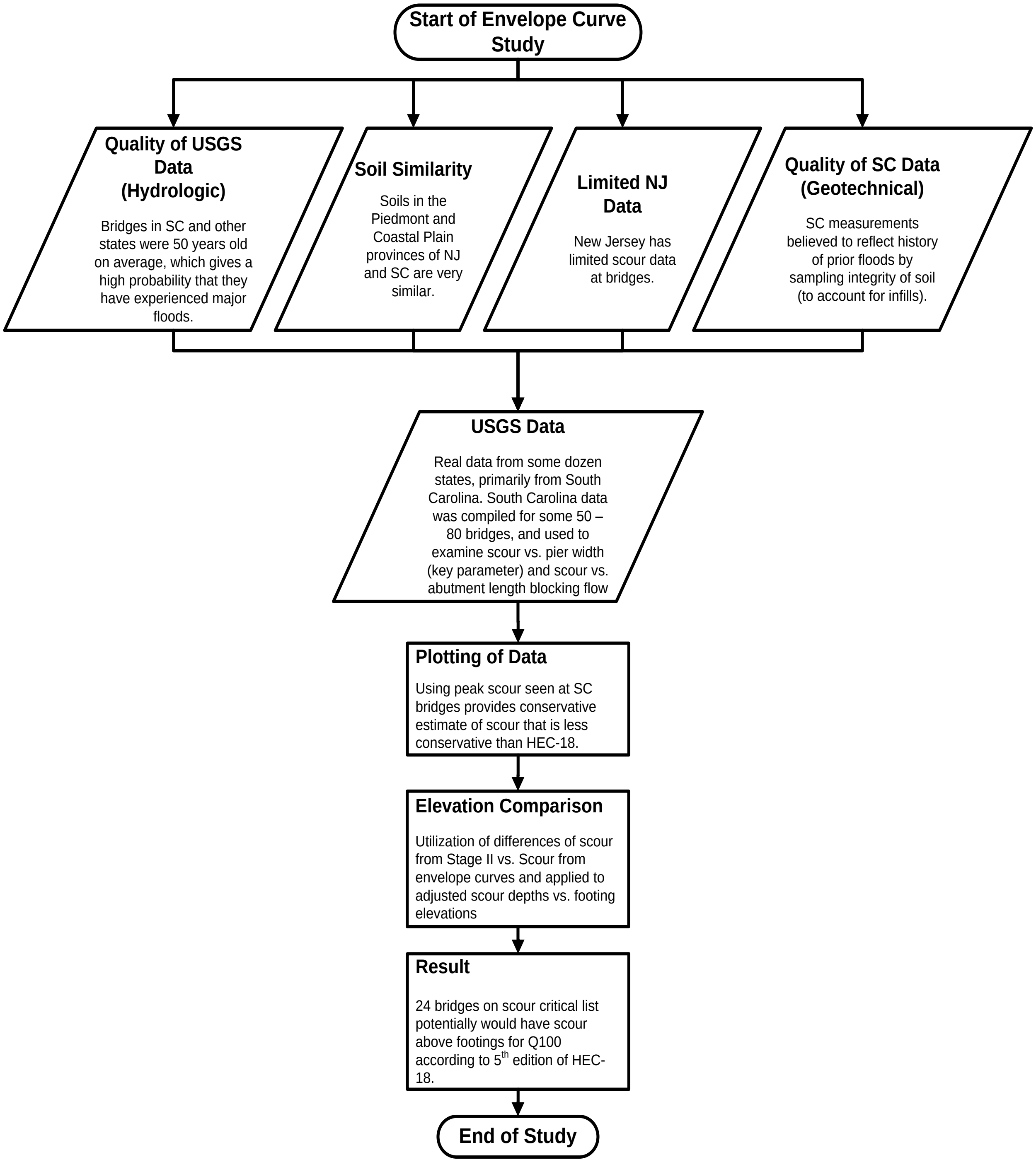


Figure 5. Process for Development and Application of New Jersey Envelope Curves

Table 5 – Summary of USGS Envelope Curve Studies Reviewed

State	**Scour Type**	**Bed Type**	**Physiographic Province**	**Scour Depth Range (ft.)**	**Median Grain Size and/or Range (mm)**	**Number of Actual Scour Measure-ments**
South Carolina	Abutment	Clear	Coastal & Piedmont	0 to 23.6	0.73 Piedmont 0.180 Coastal	209
South Carolina	Contraction	Live	Coastal & Piedmont	0 to 16.1	Median 0.59 Range: 0.18-1.7	89
South Carolina	Pier	Live	Coastal & Piedmont	1.7 to 16.9	Range: 0.24-1.7	151
National Bridge Scour Database	Pier	Live	Coastal & Piedmont	____	Median 0.54 Range: 0.12-1.82	92 (9 States)
South Carolina	Pier	Clear	Piedmont	0 to 8	Median: 0.105 Range: 0.062-0.990	87
South Carolina	Pier	Clear	Coastal	0 to 1.8	Median: 0.54 Range: <0.062-0.556	92
South Carolina	Contraction	Clear	Piedmont	0 to 4.5	Median: 0.105mm Range: 0.062-0.990	75
South Carolina	Contraction	Clear	Coastal	0 to 3.9	Median: 0.162mm Range: <0.062-0.556	64
National Bridge Scour Database	Pier	Clear & Live	Piedmont & Coastal	0 to 25	____	506
National Bridge Scour Database	Abutment	Clear & Live	Piedmont & Coastal	0 to 18	____	Limited Data
Maine	Abutment	Live	Piedmont & Coastal	0 to 6.8	Median: 4.17 Range: 0.025-7.49	100

to both pier and abutment scour in live-bed and clear-water conditions. When multiple developed envelope curves were applicable for a specific situation, all of the envelope curves were utilized to assess the ranges of their predictions. To be conservative, the curves generating the largest scour depths were used in the analysis. Note that all data and envelope curves presented in this study are for non-tidal bridges. The process and justification used to select envelope curves appropriate for New Jersey are described in **Appendix B1,** and the final recommended curves are presented in **Figures B1.11** and **B1.12**.

Based upon the Stage II data, each scour critical bridge is identified by the physiographic region, i.e. Coastal Plain, Glaciated and Non-Glaciated Piedmont, as well as the bed load transport (clear-water, live-bed); the contraction ratios; the pier widths; and the length of embankment blocking flow for the 100-year storm event. In addition, the total scour depth predicted in the Stage II Reports using HEC-18 equations consists of scour due to aggradation/degradation, local scour, and contraction scour. The total scour depths developed herein for piers and abutments utilize envelope curves for abutments and envelope curves and Stage II contraction scour data for piers. The total scour depths are then compared with the elevation of the bottom of the footings, whenever such data is available. The Stage II studies predicted scour depths and estimated abutment lengths for the 100 and 500 year flood events. The current requirements in HEC-18 require scour depth analyses associated with a 100 year event. From the aforementioned data, a spreadsheet for the critical bridges in the Coastal Plain and Piedmont Sections of New Jersey has been prepared and is shown in **Appendix B2.**

The following approach was employed to evaluate the scour elevation for bridges. If only abutments exist (i.e., no piers), the elevation associated with the total abutment scour calculated by the envelope curves employed must be an adequate distance above the bottom of the respective footing elevations for both the left and right abutments, taking into account footing thickness, bridge age, channel stability, and other considerations. The presumption is that, for abutments, the envelope curves predict the total scour, which includes both local and contraction scour.

If a bridge has abutments and piers, the calculated abutment and pier scour elevations at both abutments and at all piers must be an adequate distance above the respective footing elevations for all abutments and piers, taking into account footing thickness, bridge age, channel stability, and other considerations. Again, total pier scour is the sum of local pier scour obtained from envelope curves and contraction scour obtained by computation or from Stage II data.

Note that all bridges must be investigated for evidence of channel instability, since lateral migration of the thalweg can increase the amount of scour at a pier or an abutment. In situations where lateral migration is projected to occur over time, then the elevation difference between the thalweg and the existing channel bottom adjacent to the affected substructure must also be added to the total scour values as determined above.

From the Stage II data noted above, a spread sheet (see **Appendix B2**) was compiled for each bridge in the Coastal Plain and Piedmont Provinces that provides the bridge number, pier width (per pier scour), embankment length (for abutment scour), and scour depth (the value calculated in the Stage II reports and the value calculated using a specified envelope curve equation). The resultant scour depth elevation computed using envelope curves was compared with the footing elevation. **Table 6** shows those 23 bridges of the 102 analyzed where the resultant scour depths are above the footing elevations. Pending additional study, these 23 bridges are potential candidates for removal from the scour critical list. Note that all bridges with piers in the table have pier widths less than 6 feet.

Table 6 – Hydraulic Analysis of Bridges

Bridge Number	**Physiographic Province**	**Percentage of Q_{100} Seen?**	**Height Above Left Abutment Footing (ft.)**	**Height Above Right Abutment Footing (ft.)**	**Height Above Most Critical Pier-Footing (ft.)**	**Gage Location (On or Off Stream)**
118152	Coastal Plain	111.6	1.82	0.65	------	Off
118153	Coastal Plain	89.8	1.12	1.35	------	Off
119151	Coastal Plain	111.6	5.80	4.71	------	Off
119156	Coastal Plain	89.8	16.86*	21.62*	17.31	Off
324153	Coastal Plain	88.1	2.87	2.54	------	Off
324156	Coastal Plain	115.9	25.38*	26.02*	------	Off
408160	Coastal Plain	88.1	23.44*	24.49*	------	On
826150	Coastal Plain	89.8	1.92	1.52	------	Off
1122150	Coastal Plain	95.0	0.07	6.06	------	Off
1304156	Coastal Plain	159.9	3.13	4.55	------	On
1308154	Coastal Plain	78.3	0.04	8.16	------	On
1703152	Coastal Plain	118.9	1.73	1.73	------	On
201151	Piedmont	341.2	0.45	0.88	------	On
719151	Piedmont	93.3	4.50	5.71	------	On
722158	Piedmont	96.0	4.95	1.63	0.06	On
1218158	Piedmont	240.1	2.82	2.69	------	On
1418154	Piedmont	91.5	1.09	0.92	4.21	On
1601157	Piedmont	85.8	2.98	3.65	------	On
1601160	Piedmont	85.8	5.81	5.85	------	Off
1612154	Piedmont	83.9	2.13	1.68	------	Off
1809153	Piedmont	92.6	0.15	1.31	------	Off
1810165	Piedmont	79.5	1.18	3.46	------	Off
2003162	Piedmont	114.5	1.41	5.98	------	On

***** denotes deep piles
----- denotes no piers
Note: Computed heights in this table based on envelope curves published 2009 and earlier.

The above approach defines potential candidates for this study. In order to assess the relative risks associated with each candidate bridge, a hydraulic/hydrologic analysis is conducted for each bridge to determine whether or not the bridge has experienced a 100-year flood event during its existence, and specifically the percentage of a 100-year event that has been recorded. This data is also provided in **Table 6**. All supporting information used in the development of this table is contained in **Appendix B2.**

Procedures for Reconnaissance Hydrologic/Hydraulic Analysis

The main purpose of conducting a hydrologic/hydraulic analysis is to determine if the bridge in question has experienced a 100-year storm event. The analysis utilizes stream gage data to determine if the bridge has seen a 100-year storm.

Reports utilized for this analysis are USGS data for the gages in question and the USGS report, “Methodology for Estimation of Flood Magnitude and Frequency for New Jersey Streams, U.S. Geological Survey Scientific Investigation Report 2009-5167" by Kara M. Watson and Robert D. Schopp (2009). Storm events in 2011 and 2012, in many instances produced stream flows which were greater than many prior peak flows as shown in the 2009 Study. As a result, recalculation of the 100-year storm event by Kara Watson, NJ-USCS, was performed and provided to NJIT for this study.

When selecting stream gage(s) to be used in conjunction with specific bridges, the approach is to utilize a gage that is on the same stream or river as the bridge in question. Where multiple gages exist on the stream, the one closest to the bridge is utilized. When a gage with a flow history is available, this is called an “On Stream Hydraulic Analysis”. Information required for this analysis consists of:

- Bridge coordinates are obtained from StreamStats (http://water.usgs.gov/osw/streamstats/new_jersey.html)
- The Drainage Area from StreamStats at the bridge,
- The Q_{100} of the gage from USGS (Kara Watson, communication 2013)
- The peak flow of record at the gage from the USGS

By taking the peak flow seen at the gage since the time the bridge was constructed one can convert the peak flow recorded at the gage to a corresponding flow simulated at the bridge using the equation below:

$$Q_u = \left(\frac{DA_u}{DA_g}\right)^x \times Q_g \qquad \textbf{Eq. 1}$$

where Q_u is the flow at the ungaged bridge, Q_g is the maximum flow at the gage (since the construction of the bridge). DA_u is the drainage area at the ungaged bridge, and DA_g is the drainage area at the gage. The transfer coefficient, x, is region specific and obtained from the USGS document cited above. The bridge drainage area is obtained by inputting the bridge coordinates in StreamStats.

If the maximum recorded flow at the gage is larger than the Q_{100} estimates from the USGS, then the bridge has seen a 100-year storm. For all gages of interest, the percentage of the 100-year event is recorded for each bridge in **Table 6**.

For a bridge that does not have a gage on stream, an "Off Stream Hydraulic Analysis" is developed. The information needed for this analysis is as follows:

- Bridge coordinates are obtained from StreamStats
- The Drainage Area from StreamStats at the bridge,
- The Q_{100} of the gage from the USGS
- The peak flow of record at the gage from the USGS
- The use of StreamStats for gages with insufficient record length

Using flow data from a gage on local watercourses closest to the bridge one can compare the peak flow recorded at the gage since bridge construction with the Q_{100} estimate for the gage using StreamStats. If the gage has recorded a 100-year storm, then the bridge (in close proximity) also is presumed to have seen a 100-year storm. For all gages of interest, the percentage of the 100 year event is calculated in **Table 6**.

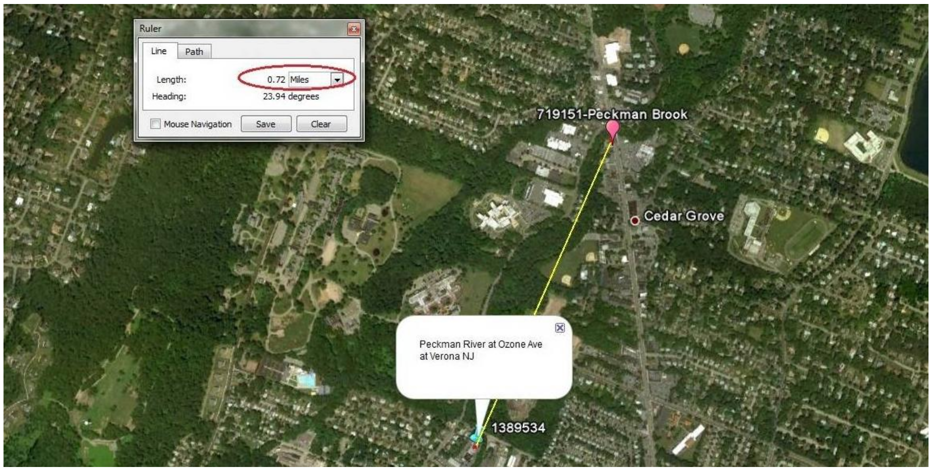
It should be noted that four off-stream gages utilized in **Table 9** had limited lengths of record (i.e. a range of three to eight years of record). The magnitude of the peak flow rates associated with Hurricane Irene on 8/28/2011, as compared to the 100-year flood event at these gages as estimated by StreamStats, demonstrated the significance of the return period of the stream flows caused by Irene.

Real-time stream flow information provided by the USGS can be found at the following URL: http://waterwatch.usgs.gov/new/?m=real&r=nj&w=real%2Cmap (WaterWatch, 2011). This website contains an interactive map of New Jersey which can be used to access data from gage locations around the State. At the bottom of the web page, there are a few options from which the user can choose. Each option, e.g. Single Station, will yield information about the selected gage. By clicking on a gage, with the 'Single Station' option chosen, the user can obtain description data for the gage under the summary tab and a rating graph under the rating tab. If the Peak flow option is selected (at the bottom) when a gage station is clicked, a chart with the peak flows for that gage along with the corresponding dates will be shown.

Example hydrologic reconnaissance analyses for selected scour critical bridges are included in **Appendix C** of this research study. **Figures 6** and **7** illustrate the Google Earth software programmed by the NJIT Scour Team to locate bridges and gages and the distances between them.

There are 102 bridges on the Scour Critical List located in the Coastal and Piedmont provinces in New Jersey. Utilizing the Envelope Curve approach any bridge that has a predicted scour depth greater than the respective footings is considered a high risk bridge.

The bridges in **Table 6** represent those located in the Coastal and Piedmont Regions where the predicted scour is above the base of the footing. The envelope curve analysis indicates that such bridges will not be undermined. These data are then used to determine hydrologic/hydraulic risk using Module 3 of the Scour Evaluation Model (SEM).



Length: 0.72 Miles
Heading: 23.94 degrees

Peckman River at Ozone Ave at Verona NJ

Figure 6. Location of Sample Bridge, Nearest Gage, and Distance Determination Using Google Earth

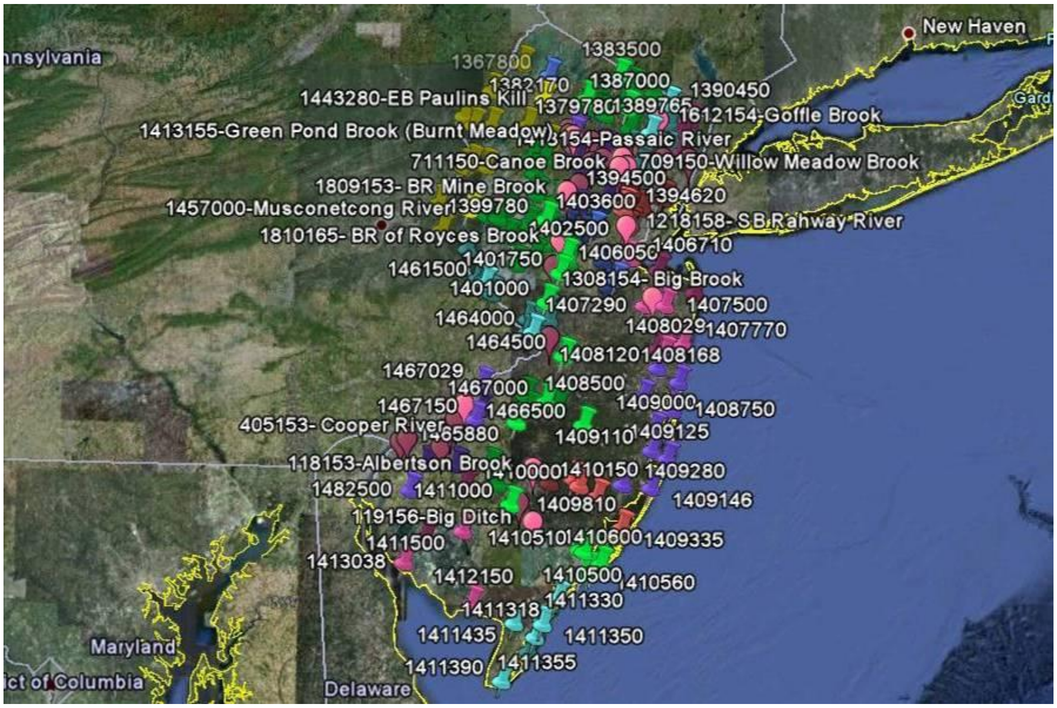


Figure 7. Statewide Location of Bridges and Gages Using Google Earth