FHWA-NJ-2017-011

Design and Evaluation of Scour for Bridges Using HEC-18

(Volume 2 of 3)

FINAL REPORT
July 2017

Submitted by

John R. Schuring, PE, PhD
Professor of Civil &
Environmental Engineering
New Jersey Institute of
Technology

Robert Dresnack, PE, PhD
Professor of Civil &
Environmental Engineering
New Jersey Institute of
Technology

Eugene Golub, PE, PhD
Professor of Civil &
Environmental Engineering
New Jersey Institute of
Technology

NJDOT Research Project Manager
Ms. Pragna Shah

In cooperation with

New Jersey
Department of Transportation
Bureau of Research
And
U.S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA-NJ-2017-011	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Design and Evaluation of Scour for Bridges Using HEC-18, Vol. 2 of 3		**5. Report Date** July 2017 **6. Performing Organization Code**
7. Author(s) John R. Schuring, Robert Dresnack, & Eugene Golub		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Civil and Environmental Engineering New Jersey Institute of Technology University Heights Newark, NJ 07102-1982		**10. Work Unit No.** **11. Contract or Grant No.** NJDOT TO-89
12. Sponsoring Agency Name and Address N.J. Department of Transportation 1035 Parkway Avenue P.O. Box 600 Trenton, NJ 08625-0600 Federal Highway Administration U.S. Department of Transportation Washington, D.C.		**13. Type of Report and Period Covered** Final Report 1/1/09- 9/30/13 **14. Sponsoring Agency Code**
15. Supplementary Notes		

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 geo-technical, 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.

17. Key Words Bridge Scour, Scour Analysis, Scour Critical Bridges	**18. Distribution Statement** No Restrictions.		
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No of Pages** 56	**22. Price**

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

This project was conducted with the support and cooperation of the New Jersey Department of Transportation and the Federal Highway Administration.

The Research Team gratefully acknowledges the contributions of:

- Project Managers Pragna Shah, Paul Thomas, Daniel LiSanti, and Nazhat Aboobaker for their guidance and skillful administration;
- Research Customers Richard Dunne, Scott Thorn, Nat Kasbekar, and Ayodele Oshilaja for their direction and strong technical insight;
- Scour Project Implementation Committee for their valued input, especially members Scott Deeck, Eddie Germain, Xiaohua “Hanna” Cheng, and Eric Kraehenbuehl;
- FHWA engineers Eric Brown (Baltimore Resource Center), Chester Kolota (NJ Division), and Dave Henderson (Washington, D.C. Office of Bridges and Structures) for their expert review and constructive comments;
- USGS New Jersey Water Science Center for their expert hydrologic support, especially Richard Kropp, Kara Watson, Blaine White, Jason Shvanda, and Robert Schopp.

We are also indebted to the student research assistants for their wonderful efforts on the project and significant contributions to this report, including Josh Tooker, Melissa Salsano, Shu Tham, Piotr Wiszowaty, Matthew Young, William Pennock, Brian Shiels, Dillion Collins, Yosef Portnoy, Abolfazl Bayat, Andrew Semanchik, and Joseph Kardos. Most have since graduated and moved into the professional world. It was our pleasure to work with them.

TABLE OF CONTENTS

VOLUME 1

Page

EXECUTIVE SUMMARY 1
INTRODUCTION 4
- **Background 4**
- **Project Objectives 5**
- **Scope and Techniques of the Research Study 6**
  - **Phase 1 - Literature Search 6**
  - **Phase 2 – Investigative Research Study 7**

SUMMARY OF NEW JERSEY'S SCOUR PROGRAM 10
- **Chronology of NJ's Scour Program 10**
- **Program Highlights and Current Status 13**

SURVEY OF SCOUR PRACTICE 16
- **Survey Methodology 16**
- **Survey Results 16**
- **Selected Best Practices of Other States 19**

REVIEW - TRADITIONAL & ALTERNATE METHODS OF SCOUR ANALYSIS 22
- **Overview of HEC-18 Scour Equations and Sources 22**
- **HEC-18 Hydrologic and Hydraulic Requirements for Scour Evaluation 24**
- **Comparative Studies of Observed vs. Predicted Scour in the U.S. 25**

GEOTECHNICAL EVALUATION OF BRIDGE SCOUR 29
- **Background 29**
- **Summary of New Jersey Geology with Comments on Scour Potential 30**
- **Description of Erosion Classes 32**
  - **Geological Materials with High Erosion Resistance 33**
  - **Geological Materials with Moderate Erosion Resistance 38**
  - **Geological Materials with Low Erosion Resistance 42**
  - **Compound and Stratified Erosion Classes 44**
  - **Long-term Channel Stability 45**
- **Geotechnical Evaluation Procedure Steps 46**
  - **Step 1- Geotechnical Reconnaissance Study 46**
  - **Step 2- Field Scour Investigation 47**
  - **Step 3 - Detailed Investigation (Optional) 48**
  - **Step 4 - Determination of Erosion Class and Scour Risk 49**

GUIDELINES - HYDROLOGIC/HYDRAULIC EVALUATION OF SCOUR RISK 50
- **Background 50**
- **Envelope Curves – Their Development and Applications to New Jersey 51**
- **Selection of Envelope Curves Appropriate to New Jersey 53**
- **Procedures for Reconnaissance Hydrologic/Hydraulic Analysis 58**

VOLUME 2

Page

NEW JERSEY SCOUR EVALUATION MODEL (SEM)... 61
- **Model Purpose and Overview 61**
- **Assigning Geotechnical Risk Level – Module 1 .... 63**
- **Assigning Hydrologic/Hydraulic Risk Level – Module 2 .... 66**
- **Risk Decision Matrix – Module 3 .... 69**
- **Bridge Importance Analysis – Module 4 .... 70**
- **Recommended Actions – Module 5.. 72**
- **Reporting Requirements for Existing Bridges 74**
- **Scour Evaluation for New Bridges 76**

EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM) 79
- **Field Visits for Validation and Calibration of the Model 79**
- **Example Model Applications to Selected Scour Critical Bridges.................... 79**

REFERENCES.. 102

VOLUME 3

Page

APPENDICES 110
- **Appendix A: Selected Scour Analysis Methods from HEC-18....................... 110**
- **Appendix B: Supplementary Materials 127**
  - **Appendix B1: USGS Envelope Curves Investigated 128**
  - **Appendix B2: Summaries of Envelope Curve Analyses and Supporting Data for the Coastal Plain & Piedmont Provinces 142**
  - **Appendix B3: Field Inspection Form for Bridge Scour Investigation..... 148**
  - **Appendix B4: Procedures for Completing the "Field Inspection Form for Bridge Scour Investigation" 155**
  - **Appendix B5: Web Survey Email Transmittal and Web Survey Form 165**

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.

LIST OF TABLES

Volume 1

	Page
Table 1 – Examples of Modified or Alternative Scour Evaluation Methods	20
Table 2 – Hydraulic Design, Scour Design, and Scour Design Countermeasure Design Flood Frequencies (Table 2.3 from Arneson et al, 2012)	25
Table 3 – Summary of Predicted vs. Observed Abutment Scour for Maine Study (modified from Lombard and Hodgkins 2008)	26
Table 4 – Definition of SEM Erosion Classes	34
Table 5 – Summary of USGS Envelope Curve Studies Reviewed	55
Table 6 – Hydraulic Analysis of Bridges	57

Volume 2

	Page
Table 7 – Priority Levels and Corresponding Recommended Actions	73
Table 8 – Common Protective Measures	73
Table 9 – Coding Guide for Bridges - Item 113	75
Table 10 – Summary of Model Input and Results for Example Bridges	81

LIST OF FIGURES

Volume 1

	Page
Figure 1. Summary of Scour Practice Survey Results	17
Figure 2. Observed vs. Predicted Scour for Original Froehlich	27
Figure 3. Physiographic Provinces of New Jersey (NJGS 2011)	31
Figure 4. New Jersey SEM Erosion Classes for Soil and Rock	33
Figure 5. Process for Development and Application of New Jersey Envelope Curves	54
Figure 6. Location of Sample Bridge, Nearest Gage, and Distance Determination Using Google Earth	60
Figure 7. Statewide Location of Bridges and Gages Using Google Earth	60

Volume 2

	Page
Figure 8. Overview Flow Chart of SEM Modules	62
Figure 9. SEM Erosion Classes for Soil and Rock	64
Figure 10. Flow Chart for Evaluation of Geotechnical Risk – Module 1	65
Figure 11. Flow Chart for Evaluation of Hydrologic/Hydraulic Risk – Module 2	68
Figure 12. Risk Decision Matrix – Module 3	69
Figure 13. Bridge Importance Analysis - Module 4	71
Figure 14. Risk Decision Matrix with Example Bridge Applications Plotted	83

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 – 5^{th} 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

NEW JERSEY SCOUR EVALUATION MODEL (SEM)

Model Purpose and Overview

This chapter describes the New Jersey Scour Evaluation Model (SEM), the major deliverable of this research study. The literature search, practice survey, and analytical phases of the study have clearly established the need to improve scour analysis procedures for New Jersey bridges. The practice of applying HEC-18 methods to all bridges has resulted in overly conservative scour depth predictions in many cases. This leads to wasted resources because bridges that are not really at risk are repaired unnecessarily or replaced prematurely. The converse is also true: bridges that are truly scour susceptible are not always discerned, which may lead to unsafe conditions during high flow events.

The overall purpose of the New Jersey SEM is to improve bridge safety and to allow NJDOT to expend repair funds more strategically. The model also assures that scour evaluations for existing and new bridges are performed in a uniform manner and are based on sound engineering practice. Preliminary results 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. More importantly, the model also prioritizes bridges by scour risk so that they can be repaired in a rational sequence.

In general, the New Jersey SEM is a tiered, parametric, risk-based decision tool. A variety of geotechnical, hydrologic, and hydraulic data are first inputted into the model for a particular bridge. These data are analyzed to determine two risk ratings, one geotechnical and the other hydrologic/hydraulic. The user then enters a two-dimensional risk decision matrix to determine the scour priority level of the bridge. The bridge “importance” is then examined to see whether the priority needs to be increased. Each priority level is then linked to recommended actions, which may range from installation of countermeasures to removal from the Scour Critical List.

The general flow of the SEM is presented as a flow chart in **Figure 8**. As indicated, the model has four main interconnected modules. The function and process of the major model components are briefly summarized below.

- ***Module 1 - Geotechnical Evaluation of Scour***
  Model analysis begins with a geotechnical evaluation of scour. This requires that the user perform certain office and field studies to collect key data, which are then analyzed. This yields a geotechnical risk rating of low, medium or high. *See report section, “Assigning Geotechnical Risk Level – Module 1” on page 63 for a complete explanation of this module.*

- ***Module 2 – Hydrologic/Hydraulic Evaluation of Scour***
  The second module of the model analysis is a hydrologic/hydraulic evaluation of scour. Again, the user performs certain office and field studies to collect key

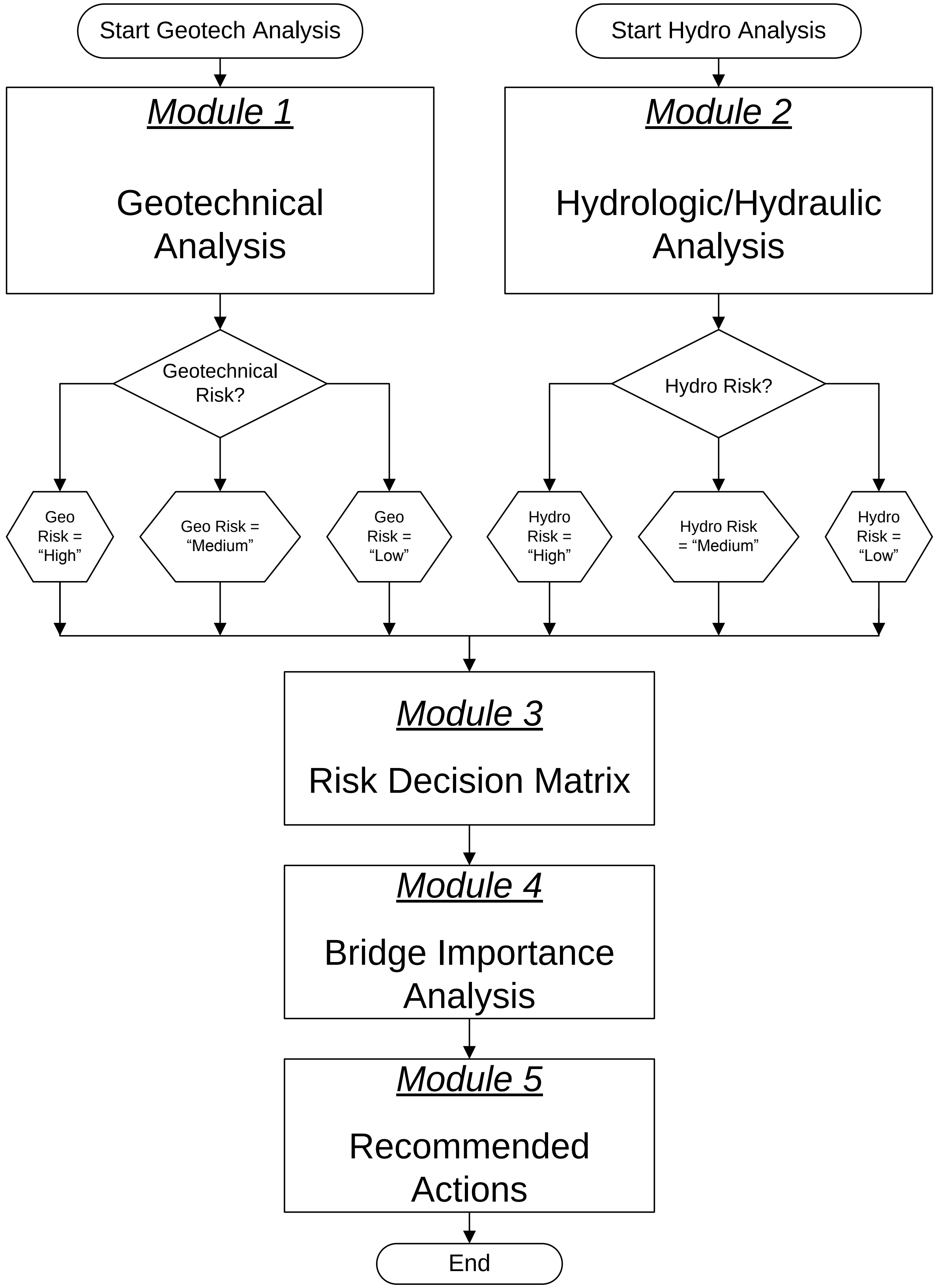


Figure 8. Overview Flow Chart of SEM Modules

data, which are then analyzed. This yields a hydrologic/hydraulic risk rating of low, medium or high.
See report section, "Assigning Hydrologic/Hydraulic Risk Level – Module 2" on page 66 for a complete explanation of this module.

- ***Module 3 – Risk Decision Matrix***
  The results of Module 1 and 2 are next inputted into Module 3. This module consists of a two-dimensional matrix that has geotechnical risk on one axis and hydrologic/hydraulic risk on the other axis. It is known as the "Risk Decision Matrix," and it generates a scour priority rating for the bridge.
  See report section, "Risk Decision Matrix – Module 3" on page 69 for a complete explanation of this module.

- ***Module 4 – Bridge Importance Analysis***
  The purpose of this module is to evaluate the "importance" of the bridge. Like the previous module, it is defined by a two-dimensional matrix, which considers average daily traffic, bridge length, and detour length, among other factors. The Bridge Importance Analysis is applied after the bridge is classified using the Risk Decision Matrix. The scour priority rating may then be adjusted depending on the calculated importance.
  See report section, "Bridge Importance Analysis – Module 4" on page 70 for a complete explanation of this module.

- ***Module 5 – Recommended Actions***
  This final module of the model links the scour priority rating with recommended corrective actions. The actions are graduated according to risk level, and they may range from priority installation of countermeasures to removal of the bridge from the Scour Critical List.
  See report section, "Recommended Actions – Module 5" on page 72 for a complete explanation of this module.

Assigning Geotechnical Risk Level – Module 1

Module 1 of the Scour Evaluation Model analyzes and determines the level of geotechnical risk for the bridge under study. The factor most influencing the geotechnical risk is the erosion resistance of the stream bed materials, as opposed to basin hydrology and channel hydraulics, which are evaluated in Module 2. So, the geotechnical risk analysis focuses on characterizing as accurately as possible the nature and condition of the soil and rock materials both upstream and underneath the bridge. This is accomplished by a combination of desk study and field investigation. In general, geological materials such as bedrock, boulders, and cobbles, normally represent lower geotechnical risk, while fine grained soils such as sand and silt, pose higher geotechnical risk. The module also considers mitigating risk factors such as evidence of field scour and bridge age.

The geotechnical risk analysis begins with both a Geotechnical Reconnaissance Study and a Field Scour Investigation. In addition, bridges may occasionally require a detailed

Geotechnical Investigation if sufficient data are not uncovered during the first two studies to confidently evaluate geotechnical risk. Procedures for conducting these investigations were previously described in report section, “Geotechnical Evaluation Procedure Steps” in chapter, “GEOTECHNICAL EVALUATION OF BRIDGE SCOUR” on page 46.

The principal objective of the investigation phases is to determine the *erosion class* of the stream bed materials. Seven distinct classes of soil and rock materials have been established for the SEM, reflecting the wide range of erosion resistance encountered in bridge scour situations. These are summarized in **Figure 9**, and each class is described in detail in report section, “Description of Erosion Classes” in chapter, “GEOTECHNICAL EVALUATION OF BRIDGE SCOUR” on page 32.

The overall procedure for assigning geotechnical risk is shown in **Figure 10**. As indicated, the results of investigative Steps 1, 2, and 3 are used to determine erosion class. Once erosion class is confirmed, a series of decisions are made to determine geotechnical risk. Decision factors include erosion class, age of the structure, and whether or not there is field evidence of substantial scour. These decisions ultimately lead to an assignment of “low,” “medium,” or “high” geotechnical risk.

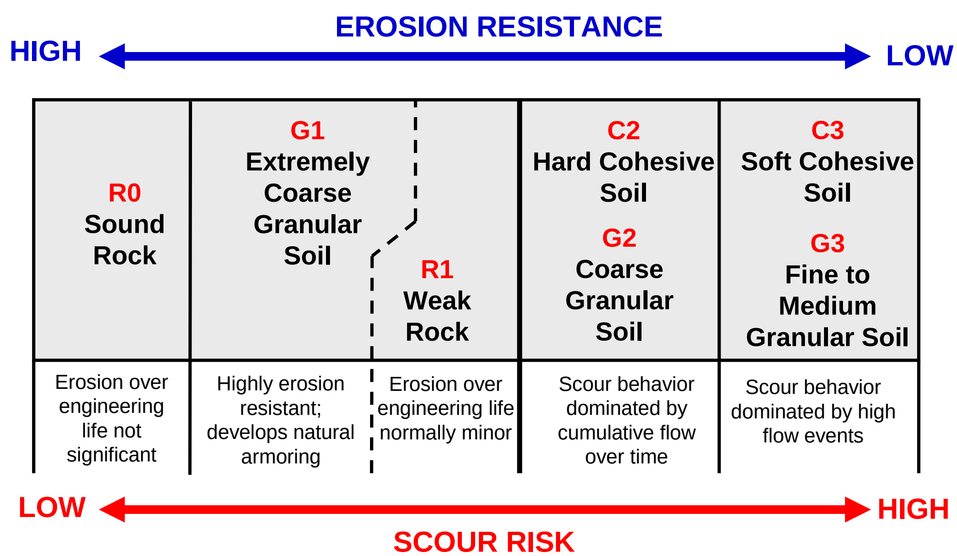


Figure 9. SEM Erosion Classes for Soil and Rock

Several logic trends are worth noting in **Figure 10**. Only bridges founded on highly erosion resistant materials, namely classes R0, R1, and G1, may be assigned to have “low” geotechnical risk. Bridges founded on materials with moderate erosion resistance (classes G2 and C2) may be assigned “medium” risk if they show no field evidence of substantial scour. Bridges founded on materials with low erosion resistance (classes G3 and C3) must be older than 50 years and show no field evidence of substantial scour to be assigned “medium” risk. Otherwise, they are assumed to have high geotechnical risk.

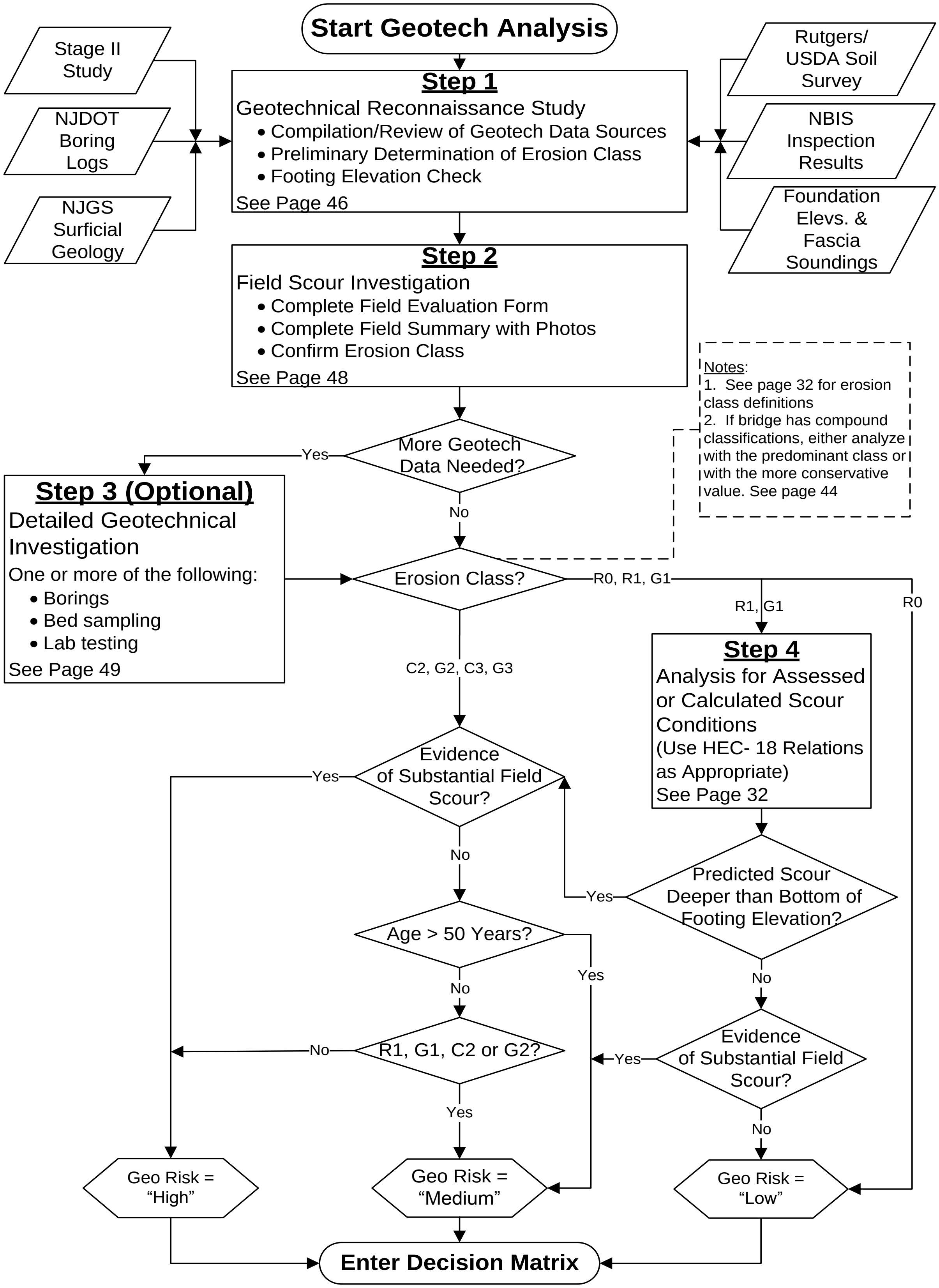


Figure 10. Flow Chart for Evaluation of Geotechnical Risk – Module 1

An important decision in both the Geotechnical and Hydrologic/Hydraiulic Risk Analyses is whether or not there is evidence of "substantial scour." This is determined during the field investigation. A number of factors enter into this determination, including depth and extent of observed scour, depth of footings, erosion class of stream bed, and existing countermeasures. Guidelines for assessing the severity of scour are provided in **Appendix B4**.

Note that the assignment of a "low" geotechnical risk rating to a bridge does not lessen the need for continued maintenance and repair of the stream channel to control scour risk. This may include removal of debris, correction of minor erosion or scour zones, or repair of existing countermeasures. Such maintenance and repair is normally accomplished using local Department crews or through standing agreements with M&R contractors.

Illustrative examples for applying Module 1 are provided in chapter, "EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM)" on page 79.

Assigning Hydrologic/Hydraulic Risk Level – Module 2

Module 2 of the Scour Evaluation Model analyzes and determines the level of hydrologic/hydraulic risk for the bridge under study. A key factor in assigning hydrologic/hydraulic risk is whether or not the bridge has experienced a 100 year storm, and if it has, how did it perform. Thus, the risk analysis also checks whether substantial field scour has been observed at the bridge. For bridges located in Coastal Plain and Non-glaciated Piedmont/Highlands physiographic provinces of the State, a supplemental analysis is also conducted using envelope curves. In general, bridges that have experienced and performed well in a 100+ year storm and/or meet the envelope curve criteria represent low hydrologic/hydraulic risk. Otherwise, they are considered to have higher hydrologic/hydraulic risk.

The hydrologic/hydraulic risk analysis begins with both a Hydrologic Reconnaissance Study and a Field Investigation Study. Note that the latter study is dual-purpose and is the same one conducted for the Module 1 Geotechnical Evaluation (see report section, "Geotechnical Evaluation Procedure Steps" on page 46). Procedures for conducting Hydrologic Reconnaissance Studies were described in report section, "Procedures for Reconnaissance Hydrologic/Hydraulic Analysis" on page 58.

An important component of Module 2 is the envelope curve analysis, which is performed for all bridges in the Coastal Plain province and any bridges in the non-glaciated section of the Piedmont/Highlands provinces. The general concept of the envelope curve is to define an upper range of observed scour depths for a given hydraulic variable within a specific physiographic region. Envelope curves developed for New Jersey's Coastal Plain and Piedmont/Highlands provinces were presented previously in chapter, "GUIDELINES - HYDROLOGIC/HYDRAULIC EVALUATION OF SCOUR RISK" on page 50.

Another important component of this module is a hydrologic reconnaissance analysis, which determines whether or not the bridge under investigation has experienced a 100-year storm (note that proportions greater than or equal to 95% are considered to satisfy the 100-year storm condition). Several data sources are used for this analysis including stream gages and StreamStats data at the bridges of interest. In general, if a bridge has experienced a 100-year storm and does not show substantial field scour, then it is deemed to have a reduced risk.

The overall procedure for assigning hydrologic/hydraulic risk is shown in flowchart form in **Figure 11**. As indicated, the results of investigative Steps 1 and 2 are related to erosion class and physiographic province. This leads to a series of decisions in which bridges are tested against the 100-year storm criterion and examined to determine whether or not there is field evidence of substantial scour. Some bridges are additionally subjected to an envelope curve analysis if they are located within select physiographic provinces. For bridges with certain kinds of bed sediments, there is a check (Step 3) of assessed or calculated scour conditions that may include appropriate HEC-18 methods. Note that for bridges on spread footings, the scour check is made relative to the bottom of footings, while for bridges on pile foundations, a lateral stability check is usually appropriate. All of these decisions ultimately lead to an assignment of “low,” “medium,” or “high” hydrologic/hydraulic risk.

Several logic trends are worth noting in **Figure 11**. Bridges founded on highly erosion resistant materials (classes R0, R1, and G1) or that have passed an envelope curve check may be assigned to “low” hydrologic/hydraulic risk. These bridges, however, must also have sustained a 100-year storm event. Conversely, any bridge in the Coastal Plain or Non-glaciated Piedmont/Highlands provinces that has a predicted scour depth greater than the respective footings is considered a “high” risk bridge. Bridges founded on materials with moderate to low erosion resistance (classes G2, C2, G3, C3) in the Highlands, Valley & Ridge, and Glaciated Piedmont provinces may be assigned either “low,” “medium,” or high” risk depending on the path through the flow chart.

Illustrative examples for applying Module 2 are provided in chapter, “EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM)” on page 79.

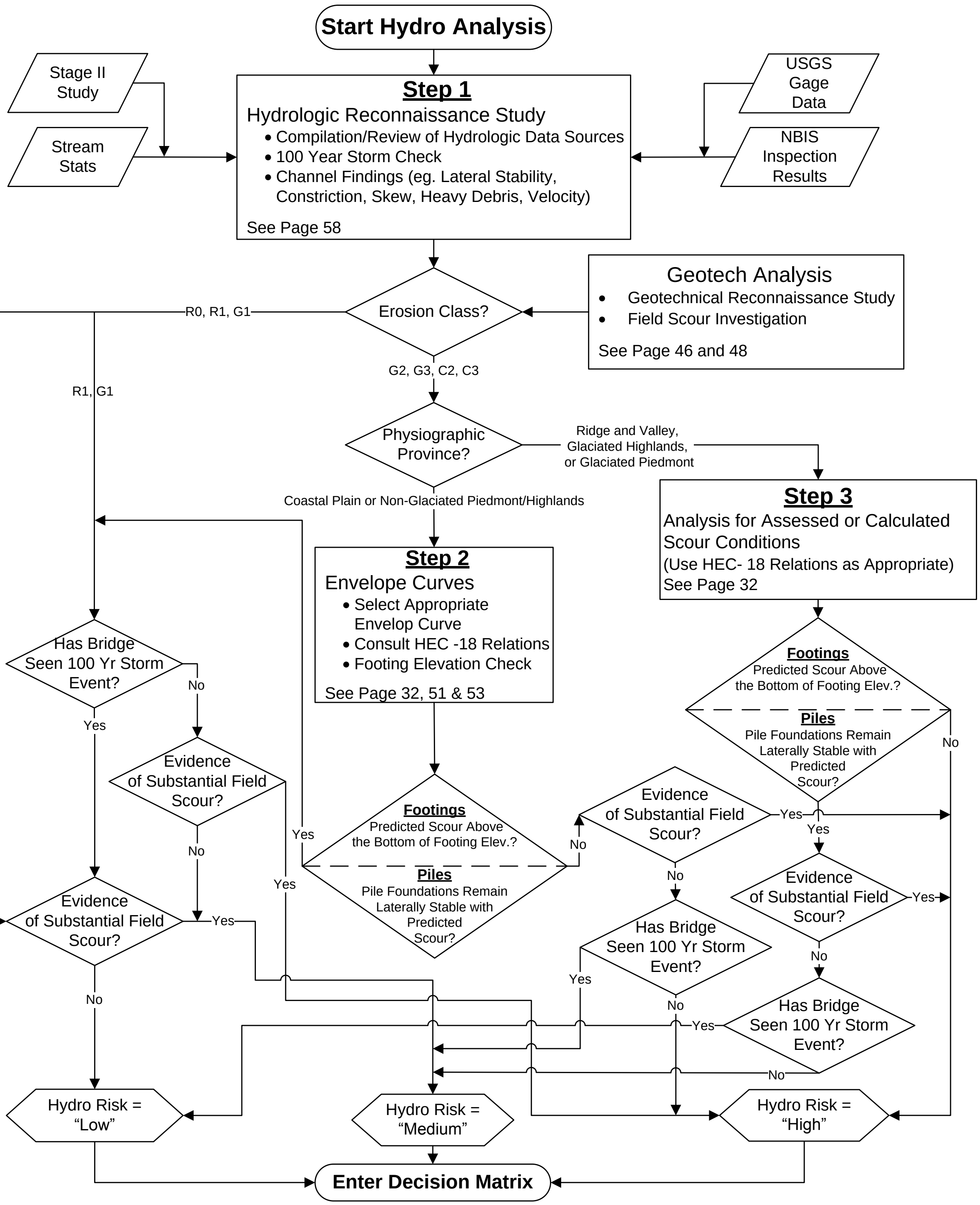


Figure 11. Flow Chart for Evaluation of Hydrologic/Hydraulic Risk – Module 2

Risk Decision Matrix – Module 3

Once the results of the Geotechnical Scour Evaluation (Module 1) and the Hydrologic/Hydraulic Scour Evaluation (Module 2) are known, these risk levels are entered into Module 3, which consists of a *Risk Decision Matrix*. A decision matrix is a technique for analyzing a multi-criteria problem like scour in a systematic way (e.g. Tague, 2004). It can consider any number of decision factors by listing them in *M* rows and *N* columns. This forms a matrix of *M x N* elements, where each element defines a certain performance or outcome. Two-dimensional decision matrices are the most common, but, in theory, they can be expanded into any number of dimensions.

The Risk Decision Matrix developed for the SEM is shown in **Figure 12**. This two-dimensional matrix has geotechnical risk on the horizontal axis and hydrologic/hydraulic risk on the vertical axis. Risk level for each argument axis is graduated from low to high. Bridges will normally plot in one of nine possible zones, each of which is associated with a scour priority rating. For example, a bridge with a "medium" geotechnical risk and a "high" hydrologic/hydraulic risk corresponds to a Scour Priority 2.

		Geotechnical Risk		
		High	**Medium**	**Low**
Hydrologic/Hydraulic Risk	**High**	Scour Priority 1	Scour Priority 2	Scour Priority 3
	Medium	Scour Priority 2	Scour Priority 3	Scour Priority 4
	Low	Scour Priority 4	Scour Priority 4	Scour Priority 4

Figure 12. Risk Decision Matrix – Module 3

There are four possible priority ratings in the Risk Decision Matrix: 1 through 4. Priority 1 corresponds to a high risk scour condition that demands prompt attention. Conversely, a bridge with a Priority 4 rating is recommended for removal from the State's Scour Critical List. The required actions for Priorities 2 and 3 are intermediate between these extremes. Note that occasionally a user may opt to plot a bridge on the borderline between two adjacent priority boxes if the bridge is judged to exhibit an intermediate level of risk. Illustrative examples for applying Module 3 are provided in chapter, "EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM)" on page 79.

Bridge Importance Analysis – Module 4

The purpose of this module is to evaluate the importance of a bridge, since some structures have more impact on the transportation network and economy than others if they should be closed. When a bridge is determined to be "important," then the Scour Priority Rating generated during Module 3 will be increased. This approach is consistent with NJDOT's Plan of Action, and it has also been employed by the Department to the seismic design of bridges, for example (FHWA 2010).

Certain bridges in NJDOT's inventory automatically default to a status of "important" because of their position within the transportation network. For example, all bridges located on the Interstate Highway System are so designated. Other situations that automatically classify a structure as important include bridges with defense priority (SHARAHNET), bridges that carry life safety utilities, bridges located on evacuation routes, and bridges providing critical hospital access. For all of these situations the bridge is automatically designated as important and scour priority will typically be increased.

A flow chart for determining whether or not the scour priority of a bridge should be modified for importance is presented in **Figure 13**. Bridges that fall into the special importance categories described in the previous paragraph, scour priority increases by one level, e.g. a Priority 2 becomes a Priority 1. Note that a Priority 1 bridge is not changed since it is already the highest priority. Similarly, a Priority 4 bridge is already recommended for removal from the Scour Critical List and is not adjusted.

For the remainder of the bridges, importance is determined analytically using the Bridge Importance Matrix or BIM, which appears in the lower left of **Figure 13** (the "No" answer branch on the chart). Like the Risk Decision Matrix in the previous module, structure importance is defined by a two-dimensional matrix**.** The parameter on the X-axis is the "Average Risk due to Failure" or ARF. Two input factors needed to compute this parameter are Average Daily Traffic (ADT) and Bridge Length. The value is defined by the following equation:

$$Average\ Risk\ due\ to\ Failure\ (ARF) = \frac{ADT\left(\frac{veh}{day}\right) * Bridge\ Length\ (ft)}{1000} \qquad \textbf{(Eq. 2)}$$

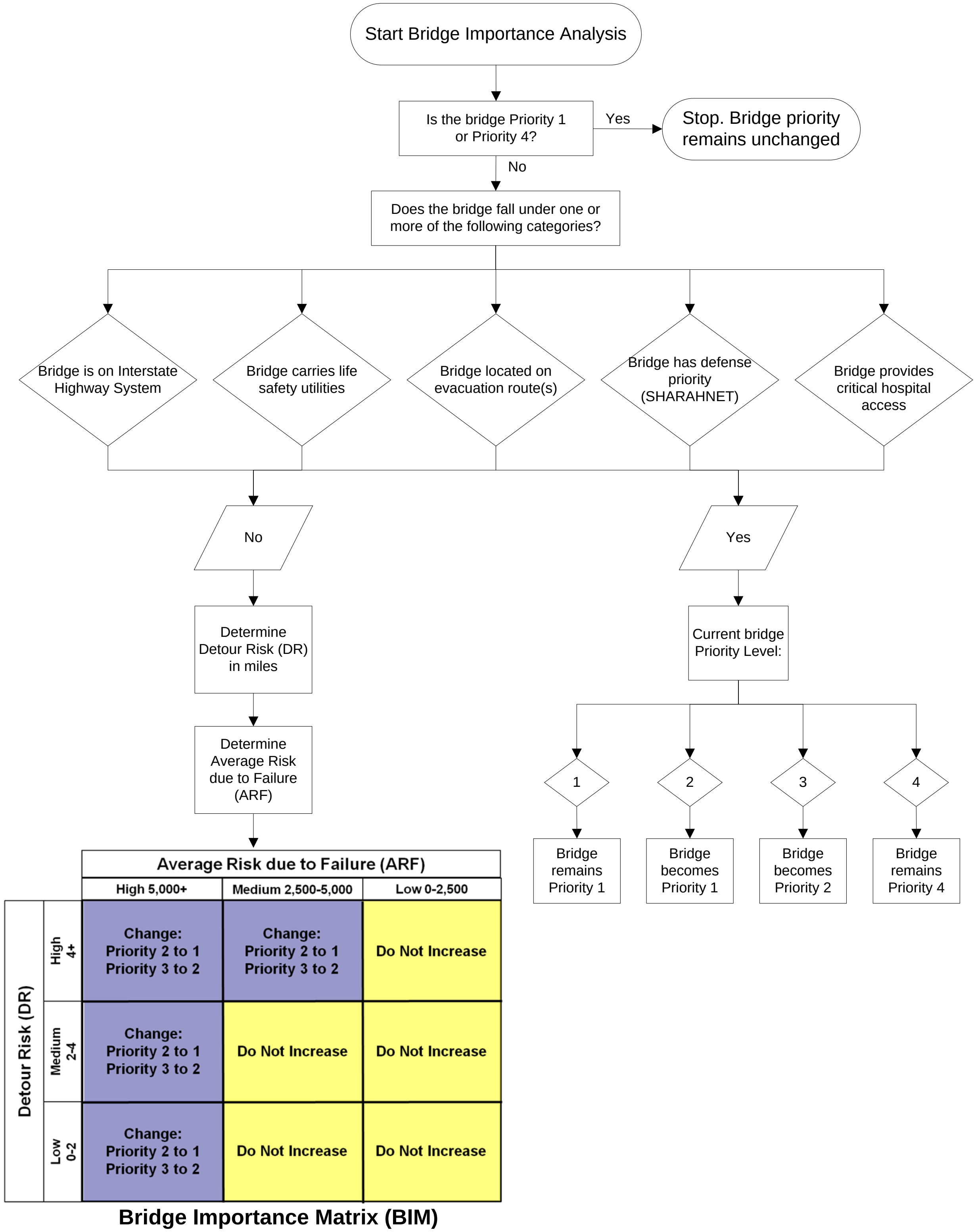


Figure 13. Bridge Importance Analysis - Module 4

Note that this parameter is generally related to the intrinsic risk to the traveling public in that it reflects the probability that a vehicle would be on the bridge if it were to fail.

The parameter on the Y-axis of the Bridge Importance Matrix is “Detour Risk” or DR. It is measured as the detour length in miles should the bridge need to be closed for repair or replacement. Detour Risk is more representative of the inconvenience to the traveling public, which translates into monetary loss due to the longer travel times. Note that the user has an option to increase the value of Detour Length to account for local traffic conditions. For example, if the posted speed limit of the detour is less, or if there is obvious congestion, then the value of Detour Length may be increased in proportion.

Once the Average Risk due to Failure and the Detour Risk parameters are computed, they are plotted on the Bridge Importance Matrix in **Figure 13** to determine whether or not the bridge is designated as important. If the bridge is found to be important, then the Scour Priority Rating is increased by one level. For example, a Scour Priority Rating of 2 from the Risk Decision Matrix is increased to a Scour Priority Rating of 1. This elevated priority assures that these bridges are moved to the front of the line in completing corrective actions. Note that, as before, if a bridge is rated as Priority 1, it is not changed since it is already the highest priority. Similarly, a bridge rated as a Priority 4 has been determined to be low risk and is recommended for removal from the scour critical list. Therefore, no adjustment is made to Priority 4 bridges.

Illustrative examples for applying Module 4 are provided in chapter, “EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM)” on page 79.

Recommended Actions – Module 5

Module 5, “Recommended Actions,” is the final module of the model. It links the priority rating with recommended actions. The actions corresponding to each Priority Level are outlined in **Table 7**. It is important that all actions listed for a given priority level be performed. Typically, all Priority 1 bridges and many Priority 2 bridges will require installation of protective measures to control scour risk. Note that FHWA now recognizes 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 a monitoring countermeasure shall retain its scour critical code.

The more common protective measures employed by the Department are listed and briefly described in **Table 8**. The table also indicates which SEM priority levels typically correspond with each protective measure. For example, traditional ‘Structural Countermeasures and Armoring’ are normally applied to Priority 1 and 2 bridges, while ‘Directed Maintenance and Repair’ is used for Priority 3 and 4 bridges.

Illustrative examples for applying Module 5 are provided in chapter, “EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM)” on page 79.

Table 7 – Priority Levels and Corresponding Recommended Actions

Priority Level	**Matrix Risk Combinations** (Geo-Hydro)	**Recommended Actions** (All listed actions for a given priority level must be performed)
Priority 1	High-High	(1) Continue flood watch or Install Real-time Monitoring System until repaired. (2) Continue annual NBIS inspection with fascia soundings until repaired. (3) Install Protective Measures as soon as possible (see Table 8).
Priority 2	High-Med Med-High	(1) Continue Flood Watch until repaired. (2) Continue annual NBIS inspection with fascia soundings until repaired. (3) Install Protective Measures (see Table 8).
Priority 3	Med-Med Low-High	(1) Continue annual NBIS inspection with fascia soundings until resolved. (2) Consider use of engineering judgment to designate the bridge as either Priority 2 or 4. (3) Alternatively, consider monitoring for an intermediate period (3± years), then revisit SEM Risk Analysis (See Table 8).
Priority 4	All Others	Bridge is recommended for removal from the Scour Critical List. Return to biannual NBIS inspection schedule. Continue M&R to control minor erosion zones and debris.

Table 8 – Common Protective Measures

Protective Measure	**Description**	**Typical SEM Priority Level**
Accelerated Bridge Replacement	May be appropriate for a high priority scour critical bridge meeting one or more of the following criteria: (1) has nearly reached the end of its design life; (2) has low NBIS value and is beyond repair; (3) has available alternate routes/detours; or (4) has limited vertical clearance which makes installation of countermeasures difficult.	1
Structural Countermeasures and Armoring	Examples include riprap (grouted and ungrouted), gabions, articulated concrete blocks, concrete pavement, and vegetation planting.	1 and 2

Table 8 – Common Protective Measures (continued)

Foundation Strengthening and Substructure Rehabilitation	Examples include underpinning, collars, sheeting, and reinforcing jackets.	1 and 2
Channel Improvement and River Training	Examples include dredging, lining, guide banks, and check dams.	1 and 2
Scour Monitoring	Long term monitoring is 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 a monitoring countermeasure shall retain its scour critical code. Long term monitoring is not permitted as a countermeasure for Priority 1 bridges.	2 and 3
Directed Maintenance and Repair	Applies to low risk bridges where limited scour or erosion damage has been observed. Maintenance and repair work is referred to the NJDOT Maintenance Office having jurisdiction (targeted riprap, gabions, ACB, etc.). Remedial work is accomplished with in-house forces or by contract.	3 and 4

FHWA requires that all scour critical bridges be coded for observed or assessed scour conditions. Bridges are coded using Item 113, which communicates as accurately as possible the current scour status of the bridge. The FHWA Item 113 Code Guide is reproduced in **Table 9**. Also shown in the table are the possible SEM priority levels corresponding to each code. Most bridges evaluated with SEM will start out as Code 3, but upon completion of the analysis, the code is elevated if the findings are favorable (SEM priority 3 or 4). Conversely, for bridges determined to have a high SEM risk level (SEM priority 1 or 2), the Code 3 rating remains until the bridge is repaired or replaced, and then it is updated.

Reporting Requirements for Existing Bridges

The overall purpose of the New Jersey SEM is to improve bridge safety and allow the NJDOT to expend repair funds strategically. First and foremost, it 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. These things are accomplished by providing standard protocols to assure that scour evaluations for bridges are performed in a uniform manner.

The Department will engage qualified consultants to perform SEM analyses of bridges using the procedure described in this report. The results are to be summarized in an "SEM Analysis and Stage III Evaluation" report generated for each individual bridge.

Table 9 – Coding Guide for Bridges - Item 113

Code	Description	Possible SEM Priority Level			
		1	2	3	4
N	Bridge not over waterway.				
U	Bridge with "unknown" foundation that has not been evaluated for scour.				
T	Bridge over "tidal" waters that has not been evaluated for scour, but considered low risk.				
9	Bridge foundations (including piles) on dry land well above flood water elevations.				
8	Bridge foundations determined to be stable for the assessed or calculated scour condition. Scour is determined to be above top of footing by assessment, by calculation or by installation of properly designed countermeasures.				X
7	Countermeasures have been installed to mitigate an existing problem with scour and to reduce the risk of bridge failure during a flood event.				X
6	Scour calculation/evaluation has not been made.				
5	Bridge foundations determined to be stable for assessed or calculated scour condition. Scour is determined to be within the limits of footing or piles by assessment, by calculations or by installation of properly designed countermeasures.			X	X
4	Bridge foundations determined to be stable for assessed or calculated scour conditions; field review indicates action is required to protect exposed foundations.			X	X
3	Bridge is scour critical; bridge foundations determined to be unstable for assessed or calculated scour conditions: (1) Scour within limits of footing or piles; (2) Scour below spread-footing base or pile tips.	X	X		
2	Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations, which are determined to be unstable by: (1) a comparison of calculated scour and observed scour during the bridge inspection, or (2) an engineering evaluation of the observed scour condition reported by the bridge inspector.	X			
1	Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic. Failure is imminent based on: (1) a comparison of calculated and observed scour during the bridge inspection, or (2) an engineering evaluation of the observed scour condition reported by the bridge inspector.	X			
0	Bridge is scour critical. Bridge has failed and is closed to traffic.				

The report will contain the following sections and must be issued by a Professional Engineer registered in New Jersey:

- Geotechnical Reconnaissance
- Hydrologic Reconnaissance
- Field Scour Investigation
- Geotechnical and Hydraulic/Hydrologic Risk Analyses
- Bridge Importance Analysis
- Scour Priority Rating
- Recommended Actions and Coding for the Bridge

In situations where the bridge is recommended for removal from the scour critical list, the report should summarize the reason(s) why the Stage II study incorrectly categorized the bridge as scour critical, e.g. new or adjusted geotechnical, hydraulic, or hydrologic information. For bridges that remain on the critical list, the report will form the basis for modifying the current Plan of Action (POA) and NBI scour coding. When it is recommended to install protective measures (priority and non-priority) or install real-time monitoring systems, the report should provide preliminary design recommendations (detailed design will be performed under separate contract). Sound engineering judgment shall be applied to all scour evaluations, as required.

Scour Evaluation for New Bridges

Although the New Jersey SEM is principally designed to evaluate the scour risk of existing bridges, many of the model components are also useful for designing new bridges. The procedure for applying the SEM to estimate scour depth for new bridges is outlined below:

<u>Step 1: Geotechnical Reconnaissance Study</u>

A thorough desk study of geologic information sources is as important for new bridges as it is for existing bridges. The study focuses on the nature of the alluvium delineated within the stream channel itself, as well as the soil/rock units that underlie and adjoin the site. Procedures for conducting the study were previously described in report section, “Step 1 - Geotechnical Reconnaissance Study” in chapter, “GEOTECHNICAL EVALUATION OF BRIDGE SCOUR” on page 46.

<u>Step 2: Detailed Geotechnical Investigation</u>

A Detailed Geotechnical Investigation is mandatory for every new bridge site (unlike existing bridges, where it is optional). In general, the subsurface investigation program shall be prepared in accordance with the “Procedures for Consultants of the Bureau of Geotechnical Engineering.” It is also important to include borings within the streambed to assess the erosion potential of the alluvial sediments. Owing to the difficulty of obtaining representative samples in certain alluvial materials, consideration should be given to use of modified investigative methods that provide data for scour evaluation. These modified methods were previously described in report section, “Step 3 - Detailed

Investigation (Optional)" in chapter, "GEOTECHNICAL EVALUATION OF BRIDGE SCOUR" on page 49.

Step 3: Determine Erosion Class

The principal objective of Steps 1 and 2 above is to determine the *erosion class* of the stream bed materials. Seven distinct classes of soil and rock materials have been detailed for the SEM, reflecting the wide range of erosion resistance encountered in bridge scour situations. These are summarized in **Figure 9** on page 64, and each class is described in detail in report section, "Description of Erosion Classes" in chapter, "GEOTECHNICAL EVALUATION OF BRIDGE SCOUR" on page 32. Once erosion class has been established, it is then linked to a method to estimate scour depth (see Step 5 below).

Step 4: Hydrologic/Hydraulic Study

This study determines the design flows for the bridge, which permits sizing of the bridge opening and estimation of channel velocities. The SEM establishes a standard protocol to conduct hydrologic analyses for both new and existing bridge sites. Several input data sources are used including stream gages, StreamStats runs, and weighted USGS flows. Procedures for conducting a hydrologic/hydraulic analysis were previously described in report section, "Procedures for Reconnaissance Hydrologic/Hydraulic Analysis" in chapter, "GUIDELINES - HYDROLOGIC/HYDRAULIC EVALUATION OF SCOUR RISK" on page 58.

Step 5: Estimate Scour Depth

The final step is to estimate the scour depth, which is needed to design the size and depth of the substructures. The SEM provides several optional methods to compute scour depth for new bridges, which are listed below. Method selection depends on physiographic province and erosion class. Note that if more than one method applies to a particular bridge, engineering judgment is recommended in the selection of scour depth for design purposes.

- ***Envelope Curve Analysis*** – If the bridge is located within the Coastal Plain or Non-glaciated Piedmont/Highlands provinces, then envelope curve analysis may be used as a verification check to estimate scour depth. An envelope curve establishes an upper range of probable scour depth for a given hydraulic variable. Envelope curves developed for New Jersey's Coastal Plain or Non-glaciated Piedmont/Highlands provinces were presented previously in report section, "Selection of Envelope Curves Appropriate to New Jersey" in chapter, "GUIDELINES - HYDROLOGIC/HYDRAULIC EVALUATION OF SCOUR RISK" on page 53.
- The method assumes that other relevant hydraulic factors are also evaluated, including channel stability, propensity of the river to move sediment, potential meandering, and the angle of attack of the river to the bridge axis. A review of

scour experience of existing bridges on the same river is also helpful, especially if the existing bridge has experienced a 100-year flood.

- ***Bed Materials with High Erosion Resistance*** - When a new bridge is to be founded on geotechnical materials that exhibit high erosion resistance, scour depth is determined by a combination of empirical rules and selected HEC-18 scour relationships. These SEM erosion classes include Sound Rock (R0), Weak Rock (R1), and Extremely Coarse Granular Soil (G1). See report section, “Geological Materials with High Erosion Resistance” in chapter, “GEOTECHNICAL EVALUATION OF BRIDGE SCOUR” on page 33 for design guidance when constructing new bridges on these geologic materials.
- ***Bed Materials with Moderate to Low Erosion Resistance*** – When a new bridge is to be founded on soils with moderate to low erosion resistance for which envelope curves are not applicable, then it is recommended that scour depth be analyzed using selected HEC-18 scour relationships. These SEM erosion classes include Coarse Granular Soil (G2), Fine to Medium Granular Soil (G3), Hard Cohesive Soil (C2), and Soft Cohesive Soil (C3). Design guidance for estimating scour depth when constructing new bridges on these geologic materials are presented in report section, “Geological Materials with Moderate Erosion Resistance” on page 38 and section, “Geological Materials with Low Erosion Resistance” on page 42, of chapter, “GEOTECHNICAL EVALUATION OF BRIDGE SCOUR”.

EXAMPLE APPLICATIONS OF THE SCOUR EVALUATION MODEL (SEM)

Field Visits for Validation and Calibration of the Model

The final phase of the research study involved validation and calibration of the newly developed New Jersey Scour Evaluation Model (SEM). Validation is a process by which the stimulation-response mechanism of the model is tested. That is, does the model represent, to a reasonable degree, the real world phenomenon that it is supposed to simulate? Calibration is a related but different process that involves the selection of threshold values for key parameters within the model, e.g. correlating grain size with erosion class.

The principal approach used in the validation and calibration phase was field evaluation of selected scour critical bridges. The idea was to analyze a bridge with the model and then correlate the results with actual observations at the site. Field visits commenced in early August 2010 and extended through December 2010. A majority of the field visits were made during summer and early fall, which are the best months to conduct scour inspections due to the prevalence of low water conditions. A total of 34 bridges were visited by the Research Team in four different physiographic provinces, including 6 in the Ridge and Valley, 14 in the Highlands, 10 in the Piedmont, and 4 in the Coastal Plain. Bridges were selected in consultation with NJDOT and the USGS. Preference was given to bridges in the northern part of the State to thoroughly test the “hard bed” classification (Erosion Classes R0 and G1), which is among the unique aspects of the new model.

A standard field inspection form was developed to record the observations of the Research Team during the field visits. 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**.

Example Model Applications to Selected Scour Critical Bridges

This section presents example applications of the SEM to 13 bridges that are currently on the State’s Scour Critical List. A number of the example bridges received a full scour evaluation including application of Modules 1 and 2 of the model. The evaluation of other bridges was more limited, since certain data were not available or complete field inspections were not conducted due to weather or other access issues. <u>**Thus, the example results presented in this section are provided for illustration purposes only. All data and risk ratings must be re-verified before undertaking any recommended actions for these bridges**</u>**.**

The 12 example bridges are listed in **Table 10** along with their physiographic province and whether they were glaciated during the Wisconsin stage, the most recent ice age. Also shown are the principal input parameters required to evaluate a bridge through each of the modules of the SEM. For example, the parameters that most affect the geotechnical evaluation (Module 1) are erosion class, bridge age, and field evidence of substantial scour. The input parameters that most affect the hydrologic/hydraulic evaluation (Module 2) are also listed in the table. One is whether the bridge has seen a 100-year flow event. Another is the result of an envelope curve analysis, which is applied to all bridges in the Coastal Plain and Non-glaciated Piedmont/Highlands. Field evidence of substantial scour also factors into the hydrologic/hydraulic evaluation.

The shaded columns of **Table 10** summarize the risk levels that resulted from each scour evaluation. These risk levels, e.g. "LOW-MED," are then plotted on the Risk Decision Matrix, which is shown as **Figure 14.** The Matrix then yields a priority rating for each bridge depending on the where it falls on the plot. The final result is a priority rating from 1 to 4, which is listed in the rightmost column of **Table 10**.

For further instruction in the application of the SEM, 2 of the 13 example bridges have been used to create detailed "Example Problems." For ease of use, the example problems have been patterned after the flow charts created for each of the modules and make use of the data contained in **Table 10**.

Example Problem 1 features the bridge on NJ Route 31 over Pequest River, Structure Number 2111155. This bridge is located in Warren County at the boundary of the Ridge and Valley and Highlands Provinces. Beginning with Module 1, the Geotechnical Reconnaissance Study and Field Scour Investigation determined that the stream bed for this bridge is composed of sediments with high erosion resistance that classify as G1. Continued analysis found the bridge to be of "Low" risk based on the fact that the footings were deeper than the calculated scour depth. In Module 2, the bridge was assessed to also have "Low" hydrologic/hydraulic risk because it had seen the 100-year storm and showed no evidence of substantial scour. In the Risk Decision Matrix (Module 3), The bridge was determined to be a Priority 4. The Bridge Importance Flow Chart (Module 4) was not applied since the bridge is already recommended for removal from the critical list. Finally, the recommended actions were determined from Module 5.

Example Problem 2 highlights the bridge on US Route 322 over Scotland Run, structure Number 826150. This bridge, located in Gloucester County, is an example of SEM analysis in the Coastal Plain. Beginning with Module 1, the Geotechnical Reconnaissance Study and Field Scour Investigation determined that the stream bed for this bridge is composed of sediments with low erosion resistance that classify as G3. Continued analysis found the bridge to be of "High" geotechnical risk because of the stream bed composition and the fact that the age was less than 50 years old. Because the bridge is located within the Coastal Plain, it was a candidate for envelope curve analysis as seen in Module 2. The bridge met the envelope criteria satisfactorily, but it had not yet seen a 100-year storm. The conclusion of this Module was that the bridge was of "Medium" hydrologic/hydraulic risk. In the Risk Decision Matrix (Module 3), Bridge 826150 was found to be a Priority 2. The Bridge Importance Flow Chart (Module 4) was next applied, but no adjustment in priority level was indicated on account of the low ADT. Finally, the recommended actions were determined from Module 5.

Table 10 – Summary of Model Input and Results for Example Bridges

	Bridge Name (Number)	Physiograaphic Province	Wisconsinan Glaciation	Geotechnical Scour Evaluation (Module 1)			Hydrologic/Hydraulic Scour Evaluation (Module 2)		Risk Decision Matrix			BIM	
				Erosion Class?	**> 50 Years Old?**	**Field Evidence of Substantial Scour?**	**Q_{100} Seen?** (proportion) ***	**Envelope Curve OK?**	**Geo Risk**	**Hydro Risk**	**Matrix Result**	**Result**	**Final**
1	Rt. 10 over Malapardis Brook (1402150)	Piedmont/ Highlands	Yes	G1	Yes	No	Yes (95.5%)	N/A	LOW	LOW	Priority 4	N/A	Priority 4
2	Rt.15 over Beaver Run (1922150)	Ridge & Valley	Yes	G1	Yes	No	Yes (138.2%)	N/A	LOW	LOW	Priority 4	N/A	Priority 4
3	Rt. 23N over Pequannock River (1605175)	Highlands	Yes	G1	No	No	Yes (115.3%)	N/A	LOW	LOW	Priority 4	N/A	Priority 4
4	Rt. 31 over Pequest River (2111155)	Ridge & Valley/ Highlands	Yes	G1	Yes	No	Yes (100.5%)	N/A	LOW	LOW	Priority 4	N/A	Priority 4
5	Rt. 33 over Manalapan Brook (1304156)	Coastal Plain	No	G3/C3	Yes	Yes	Yes (159.9%)	Yes	HIGH	MED	Priority 2	Do Not Increase	Priority 2
6	Rt. 206 over Albertson Brook (0118153)	Coastal Plain	No	G3	Yes	No**	No (87.7%)	Yes	MED	MED	Priority 3	Do Not Increase	Priority 3

* Erosion class based on study of NJGS Surficial Geology maps and the findings recorded in the Stage II report.

** Evidence of scour based on findings recorded in the Stage II report. Field inspection not conducted for this bridge.

*** Proportions greater than or equal to 95% may be considered to satisfy the Q_{100} condition.

ǂ Proportion from an off-stream analysis

Table 10 – Summary of Model Input and Results for Example Bridges (continued)

	Bridge Name (Number)	Physiogr-aphic Province	Wisconsinan Glaciation	Geotechnical Scour Evaluation (Module 1)			Hydrologic/Hydraulic Scour Evaluation (Module 2)		Risk Decision Matrix			BIM	
				Erosion Class?	> 50 Years Old?	Field Evidence of Substantial Scour?	Q_{100} Seen? (proportion) ***	Envelope Curve OK?	Geo Risk	Hydro Risk	Matrix Result	Result	Final
7	Rt. 46E over Branch of Mine Brook (1407153)	Highlands	No	G1	Yes	No	Yes (204.8%)ǂ	N/A	LOW	LOW	Priority 4	N/A	Priority 4
8	Rt. 46 over Musconetcong River (2108162)	Highlands/ Ridge & Valley	No	G1	Yes	No	No (94.4%)	N/A	LOW	MED	Priority 4	N/A	Priority 4
9	Rt. 206 over Cruisers Brook (1810155)	Piedmont	No	R1	Yes	No	Yes (176.0%)ǂ	N/A	LOW	LOW	Priority 4	N/A	Priority 4
10	Rt. 206 over Branch of Big Flat Brook (1912158)	Ridge & Valley	Yes	G1→G3 Use G2	Yes	Yes	Yes (123.9%)	N/A	HIGH	HIGH	Priority 1	N/A	Priority 1
11	Rt. 322 over Hospitality Brook (119151)	Coastal Plain	No	G3*	Yes	No**	Yes (106.3%)ǂ	Yes	MED	LOW	Priority 4	Do Not Increase	Priority 4
12	Rt. 322 over Scotland Run (826150)	Coastal Plain	No	G3*	No	No**	No (89.8%)ǂ	Yes	HIGH	MED	Priority 2	Do Not Increase	Priority 2

* Erosion class based on study of NJGS Surficial Geology maps and the findings recorded in the Stage II report.
** Evidence of scour based on findings recorded in the Stage II report. Field inspection not conducted for this bridge.
*** Proportions greater than or equal to 95% may be considered to satisfy the Q_{100} condition.
ǂ Proportion from an off-stream analysis

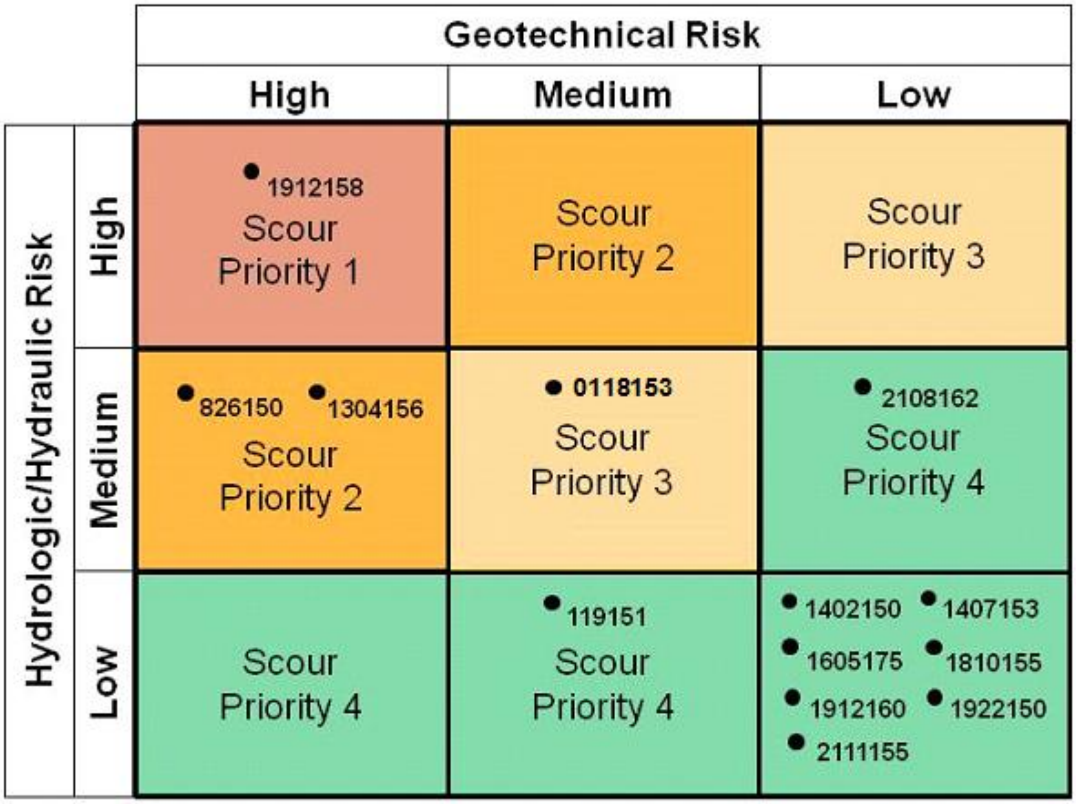
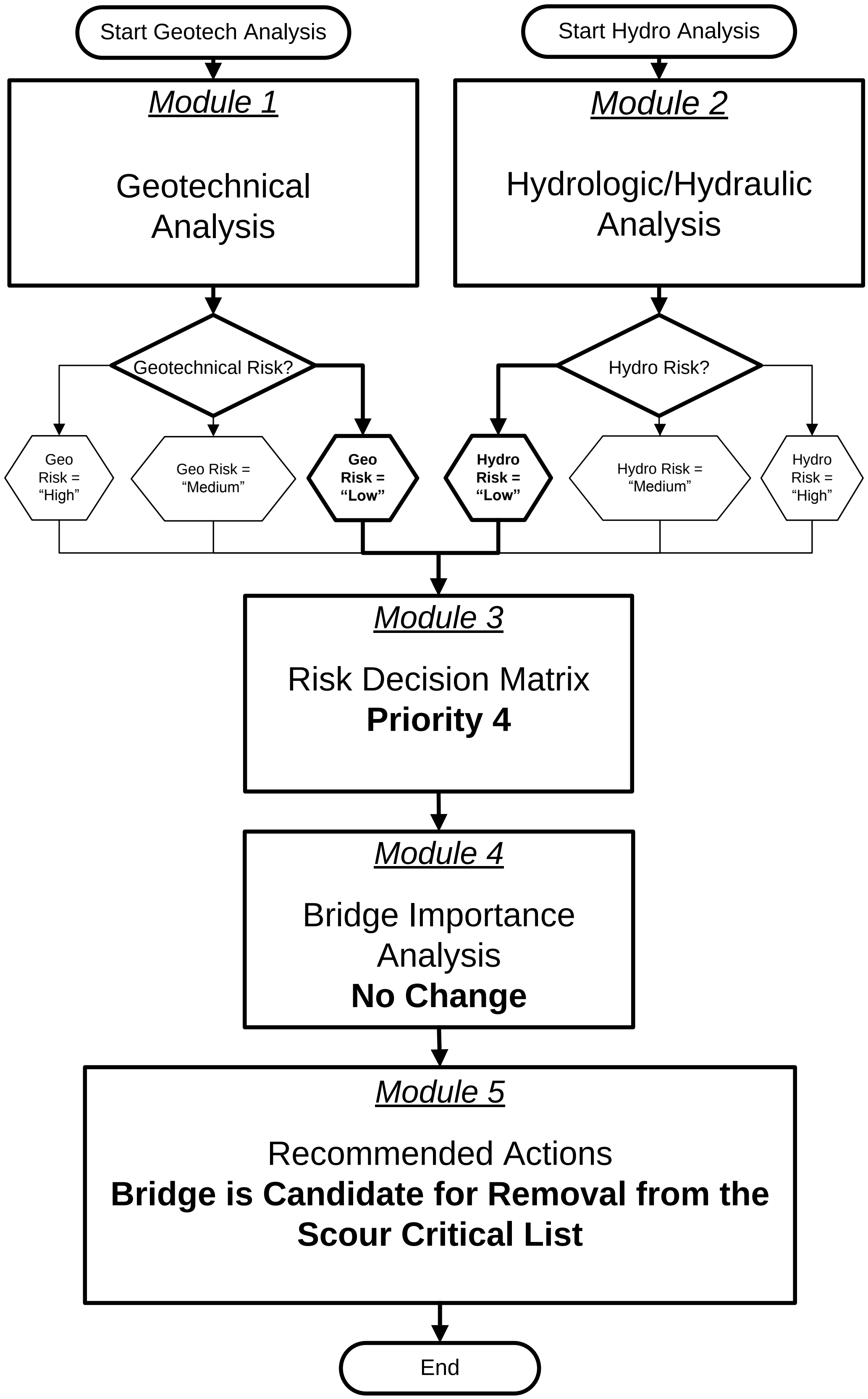


Figure 14. Risk Decision Matrix with Example Bridge Applications Plotted

Example Problem 1: Bridge 2111155

OVERVIEW OF EXAMPLE PROBLEM 1



Example Problem 1: Bridge 2111155

MODULE 1 – GEOTECHNICAL ANALYSIS

Start Geotech Analysis
NJ Route. 31 over Pequest River
White Township, Warren County New Jersey
(2111155)

Step 1

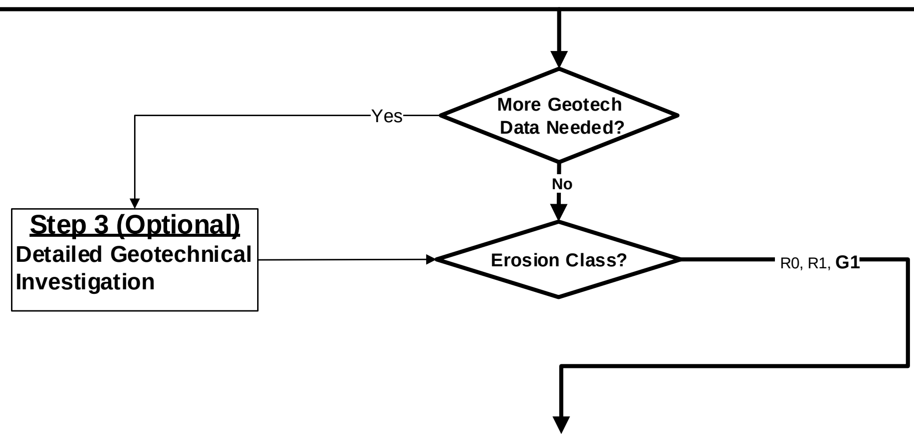
Geotechnical Reconnaissance Study Results:

- Stage II:
  - Built in 1922, two span, total length 116 ft; reinforced concrete gravity vertical wall abutments. Reinforced concrete solid wall with square nose/tail pier with spread footings.
  - Bridge determined to be scour critical based on calculated scour depth according to HEC-18 formulations.
  - Field observations found no undermining of foundations nor exposure of footings.
  - Two bed samples recovered by hand auguring to depth of between two and three feet. Could not go deeper due to presence of solid rock (either large boulder or bedrock). D_{50} likely underestimated due to presence of large boulders and cobbles.
  - Grain analysis found a sand and gravel with cobbles layer above fine to coarse sand with some gravel, silt and clay.
- USGS Surficial Geology: Alluvium (Qal), artificial fill (af), moraine deposits (Qwm), and glacial lake deltaic deposits (Qwld); general texture: silt to gravel with cobbles and boulders.
- Rutgers Soil Survey: Recent alluvium (AR) and glacial terminal moranie (GMM-24ge); general texture: clay to sandy gravel with possible cobbles and boulders.
- USDA Web Soil Survey: Fredon-Halsey complex (FrdAb); general texture: silt loam to extremely gravelly loamy coarse sand.
- NJDOT GDMS Borings: General texture: silt and clay to sand with gravel, cobbles, and boulders.
- **Conclusion**: Consensus of bed texture is silty and clay to sand with gravel, cobbles, and boulders. No evidence of substantial field scour.

Step 2

Field Scour Investigation Results:

- Stream Bed Classification and Field Description: G1 - Extremely Coarse Granular (highly erosion resistant); predominantly boulders and cobbles, some gravel to fines. Consistent upstream to downstream. Probing indicates that bed ranges from firm to hard.
- General Channel Observations: Channel profile is currently stable; banks are lined with natural cobbles, boulders, and vegetation and are stable; upstream banks are well wooded and debris-trapping potential is judged low due to high vertical clearance and low channel contraction; Upstream skew is low (<15 deg.)
- Scour Observations: One minor scour zone, measuring approx. 1 ft. in depth and 6 SF was noted at the downstream end of the center pier. The footing is not exposed and the area appears stable with some natural armoring present.
- Conclusions Related to Scour: Overall geotechnical risk is considered low. Streambed materials are highly erosion resistant and bed profile beneath and in immediate vicinity of bridge is stable. No maintenance and repair suggestions related to scour.



Continue to Step 4

Example Problem 1: Bridge 2111155

MODULE 1 – GEOTECHNICAL ANALYSIS (*Continued*)

Step 4

Analyze Scour Using Selected HEC-18 Relations: (See Chapter 6.3 and Appendix 1)

Erosion class is G1. From hydrologic/hydraulic data, assume, water Elev. for 100 year storm is 381.70 ft.

Pier Scour: HEC-18 Eq. 7.34:

$D_{50} = 0.83$ ft; $D_{84} = 1.3$ f; $\sigma = 1.57$; $K_1 = 1.1$; $K_2 = 1.33$; a = 7 ft; $y_1 = 5.4$ ft (381.70 ft – 376.30 ft);
$V_1 = 8.6$ fps; $s_g = 2.65$; $g = 32.2$ ft/s^2

H = Densimetric particle Froude Number $= \dfrac{V_1}{\sqrt{g(S_g-1)D_{50}}}$

y_s = depth of scour $= y_s = 1.1 K_1 K_2 a^{0.62} y_1^{0.38} \tanh(H^2/(1.97\sigma^{1.5}))$

$$H = \frac{V_1}{\sqrt{g(S_g-1)D_{50}}} = \frac{8.6}{\sqrt{32.2(2.65-1)*.83}} = 1.295 \qquad \tanh\left(\frac{H^2}{1.97\sigma^{1.5}}\right) = \tanh\left(\frac{1.295^2}{1.97*1.57^{1.5}}\right) = 0.4076$$

$$y_s = 1.1K_1K_2a^{0.62}y_1^{0.38}\tanh\left(\frac{H^2}{1.97\sigma^{1.5}}\right) = 1.1*1.1*1.33*7^{0.62}*5.4^{0.38}*0.4076 = 4.16 \text{ ft}$$

Contraction Scour: HEC-18 Equations. 6.1 and 6.4

$V_c = K_u y^{\frac{1}{6}} D_{50}^{\frac{1}{3}}$ $\qquad K_u = 11.17$ (English); Assume $y = y_1$

$V_c = (11.17)(5.4)^{\frac{1}{6}}(0.83)^{\frac{1}{3}} = 13.9\ \frac{ft}{sec}$

Compare V_c with V_1, $\quad 13.9 > 8.6$, $\quad$ use clear water.

$$y_2 = \left(\frac{K_u Q^2}{D_m^{\frac{2}{3}} W^2}\right)^{\frac{3}{7}} \qquad K_u = 0.0077 \text{ (English)};\ W = 58.0\,ft\ (At\ the\ Bottom) \quad D_m = 1.25 * D_{50} = (1.25)(0.83) = 1.038\,ft \quad Q = 2630\ \frac{ft^3}{sec}$$

$$y_2 = \left(\frac{(0.0077)(2630)^2}{(1.038)^{2/3}(58.0)^2}\right)^{\frac{3}{7}} = 3.22$$

$y_s = y_2 - y_0 = 3.22 - 5.4 = -2.18\,ft$ $\qquad$ Negative Value, So No Contraction Scour

So, Total Pier Scour $= 4.16\,ft$

Lowest existing bed elevation near pier is 376.3 ft.; Bottom of footing elevation is 369.1 ft;

Therefore, 376.3 – 4.16 = 372.14 ft

372.14 ft > 369.1 ft $\qquad$ OK, sufficient cover for scour resistance.

Abutment Scour: HEC 18 Eq. 8.6 (NCHRP 24-20, clear water):

$y_s = y_{max} - y_0 \qquad y_{max} = \alpha_B y_c \qquad y_c = \left(\dfrac{q_{2f}}{K_u D_{50}^{1/3}}\right)^{6/7}$

Flow, Q = 2630 ft^3/sec; $K_u = 11.17$ (English); Width at constriction = 68.1 ft; Width at Bridge = 58.0 ft.

$q_{2f} = \dfrac{Q}{w} = \dfrac{2630}{58.0} = 45.3\dfrac{\text{cfs}}{\text{ft}}$ (unit discharge at bridge opening) $\quad q_f = \dfrac{Q}{w} = \dfrac{2630}{68.1} = 38.6\dfrac{\text{cfs}}{\text{ft}}$ (unit discharge upstream)

Contraction ratio $= \dfrac{q_{2f}}{q_f} = \dfrac{45.3}{38.6} = 1.17$ From Fig. 8.12, HEC-18: $\alpha_B = 2.6$

$$y_c = \left(\frac{q_{2f}}{K_u D_{50}^{1/3}}\right)^{\frac{6}{7}} = \left(\frac{45.3}{11.17*0.83^{\frac{1}{3}}}\right)^{6/7} = 3.37 \text{ ft} \qquad y_{max} = \alpha_B y_c = (2.60)(3.37) = 8.93 \text{ ft}$$

Left Abutment: Lowest existing bed elevation near abutment is 377.8 ft.

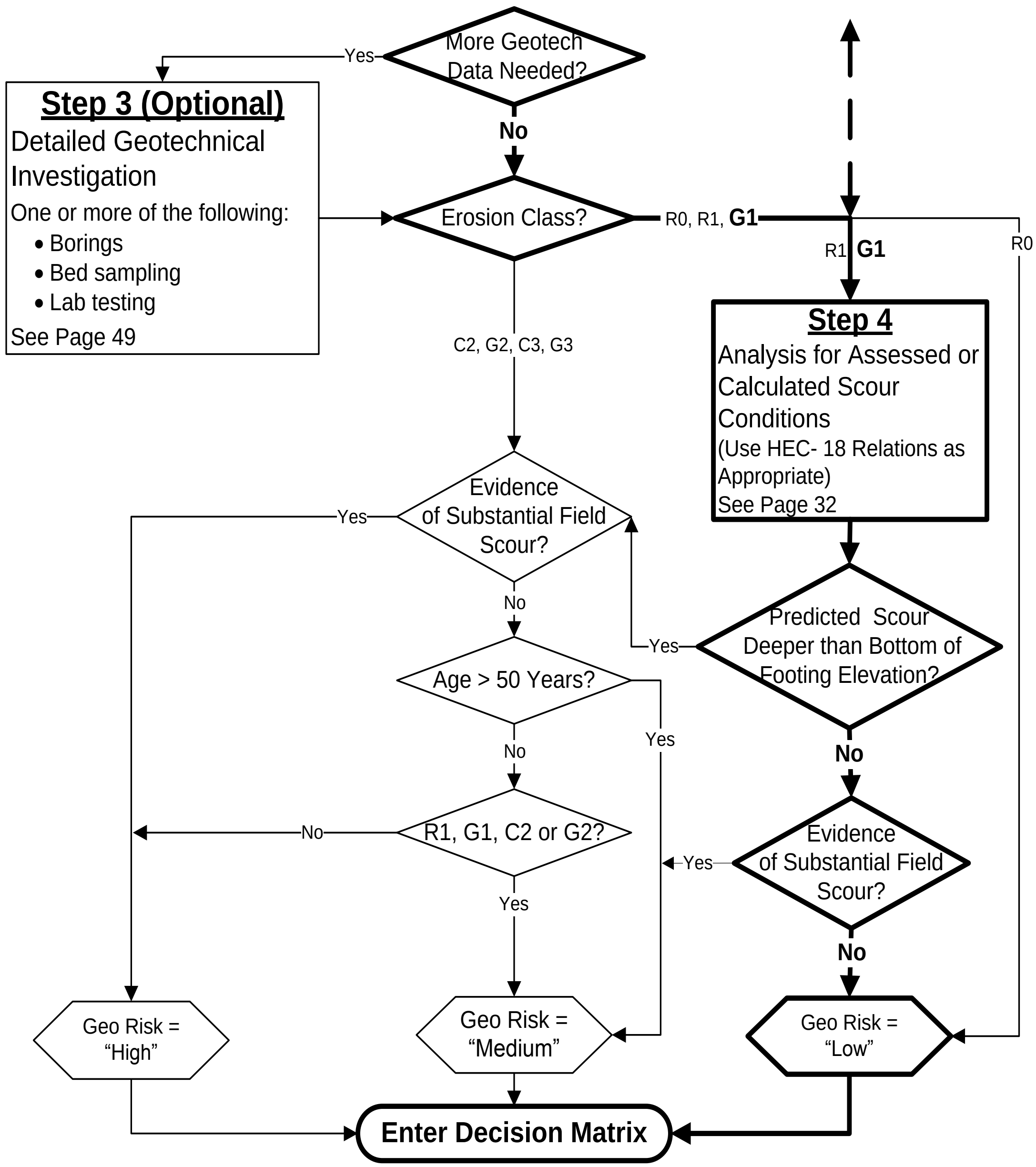
Bottom of footing elevation is 369.1 ft $\qquad$ Water depth: 381.70-377.80 = 3.9 ft

$y_s = y_{max} - y_0 = 8.75 - 3.9 = 4.85$ ft $\qquad \mathbf{377.8\,ft - 4.85\,ft = 372.95\,ft > 369.1\,ft}$

OK, sufficient cover for scour resistance. Right abutment not in main channel, say OK.

Example Problem 1: Bridge 2111155

MODULE 1 – GEOTECHNICAL ANALYSIS (*Continued*)



Example Problem 1: Bridge 2111155

MODULE 2 – HYDROLOGIC/HYDRAULIC ANALYSIS

Start Hydro Analysis
NJ Route 31 over Pequest River
White Township, Warren County New Jersey
(2111155)

Step 1
Hydrologic Reconnaissance Study:

- Background:
  - Constructed in 1922
  - There is a stream gage installed 1.1 miles upstream of the bridge (USGS01445500)
  - Largest flow of record seen at USGS 01445500= 2,370 cfs on 9/8/2011
- Stage II Data:
  - Q_{50} = 2,010 cfs Q_{100} = 2,372 cfs Q_{500} = 3,025 cfs
  - Drainage area not specified
- StreamStats Results:
  - Drainage area at bridge= 114 sq. mi.
- USGS Gage Data (01445500):
  - Drainage area at gage= 106 sq. mi.
  - Q_{100} = 2,358 cfs as per USGS extreme value analysis at gage 01445500
  - Q_{100} at bridge= 2,358 $(114/106)^{0.59}$ = 2,461 cfs
  - Percent of Q_{100} seen at the gage= (2,370/2,358)*100 = 100.5%

Conclusion: Bridge has seen 100.5% of Q_{100}

Geotech Analysis

From Geotech Analysis

Steps 1 & 2

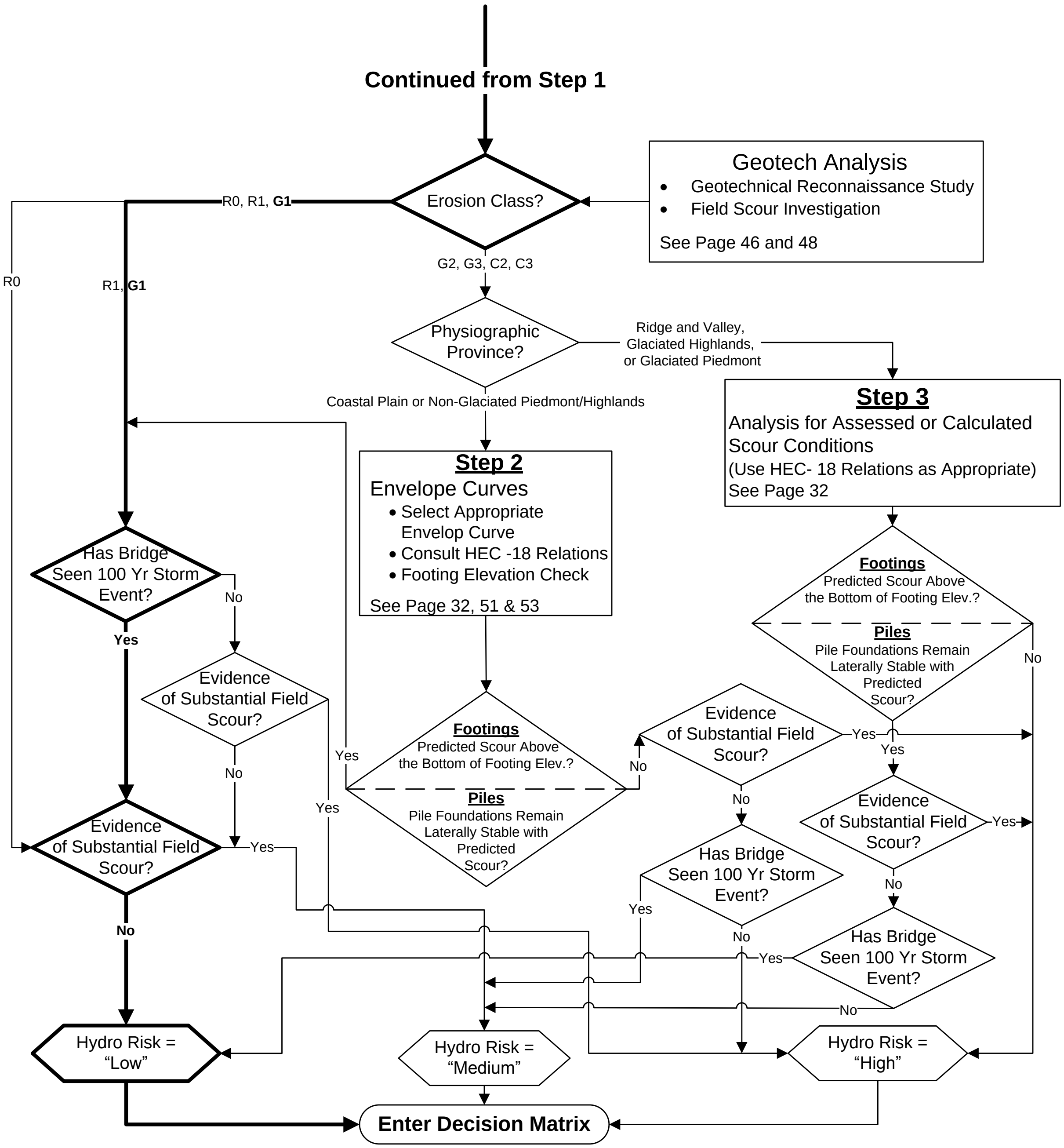
Field Scour Investigation
Parameters critical to Hydro Analysis:

- G1 – Extremely Coarse Granular
- No evidence of substantial field scour
- Ridge & Valley/ Highlands

Continue to Erosion Class

Example Problem 1: Bridge 2111155

MODULE 2 – HYDROLOGIC/HYDRAULIC ANALYSIS (*Continued*)



Example Problem 1: Bridge 2111155

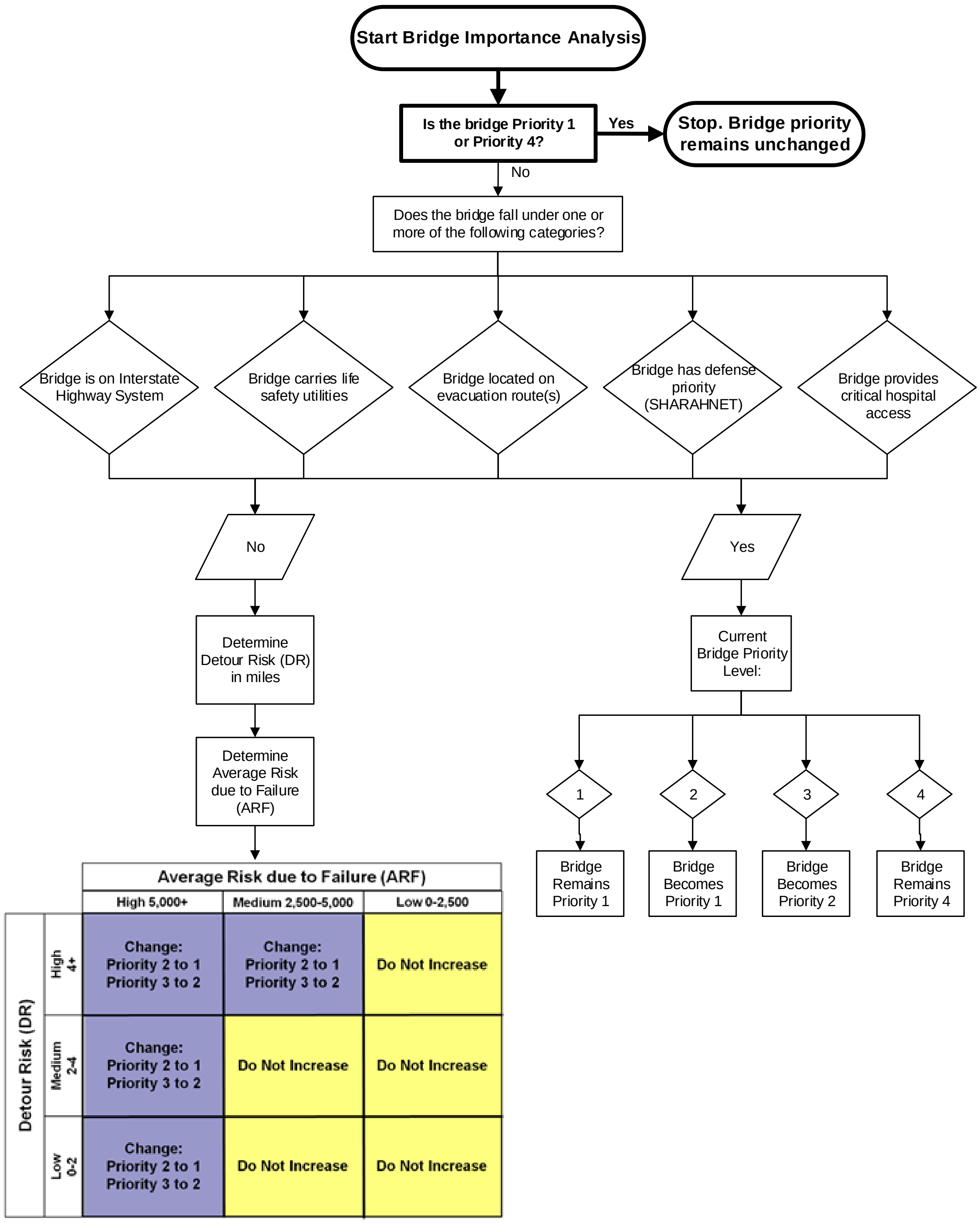
MODULE 3 – RISK DECISION MATRIX

Hydrologic/Hydraulic Risk	Geotechnical Risk: High	Geotechnical Risk: Medium	Geotechnical Risk: Low
High	Scour Priority 1	Scour Priority 2	Scour Priority 3
Medium	Scour Priority 2	Scour Priority 3	Scour Priority 4
Low	Scour Priority 4	Scour Priority 4	● Bridge 2111155 Scour Priority 4

Example Problem 1: Bridge 2111155

MODULE 4 – BRIDGE IMPORTANCE ANALYSIS

Enter the Bridge Importance Flow Chart shown below. Since bridge 2111155 is already a Scour Priority 4, it remains unchanged. Priority 4 bridges are already candidates for removal from the Scour Critical List.



Bridge Importance Matrix (BIM)

Example Problem 1: Bridge 2111155

MODULE 5 – RECOMMENDED ACTIONS

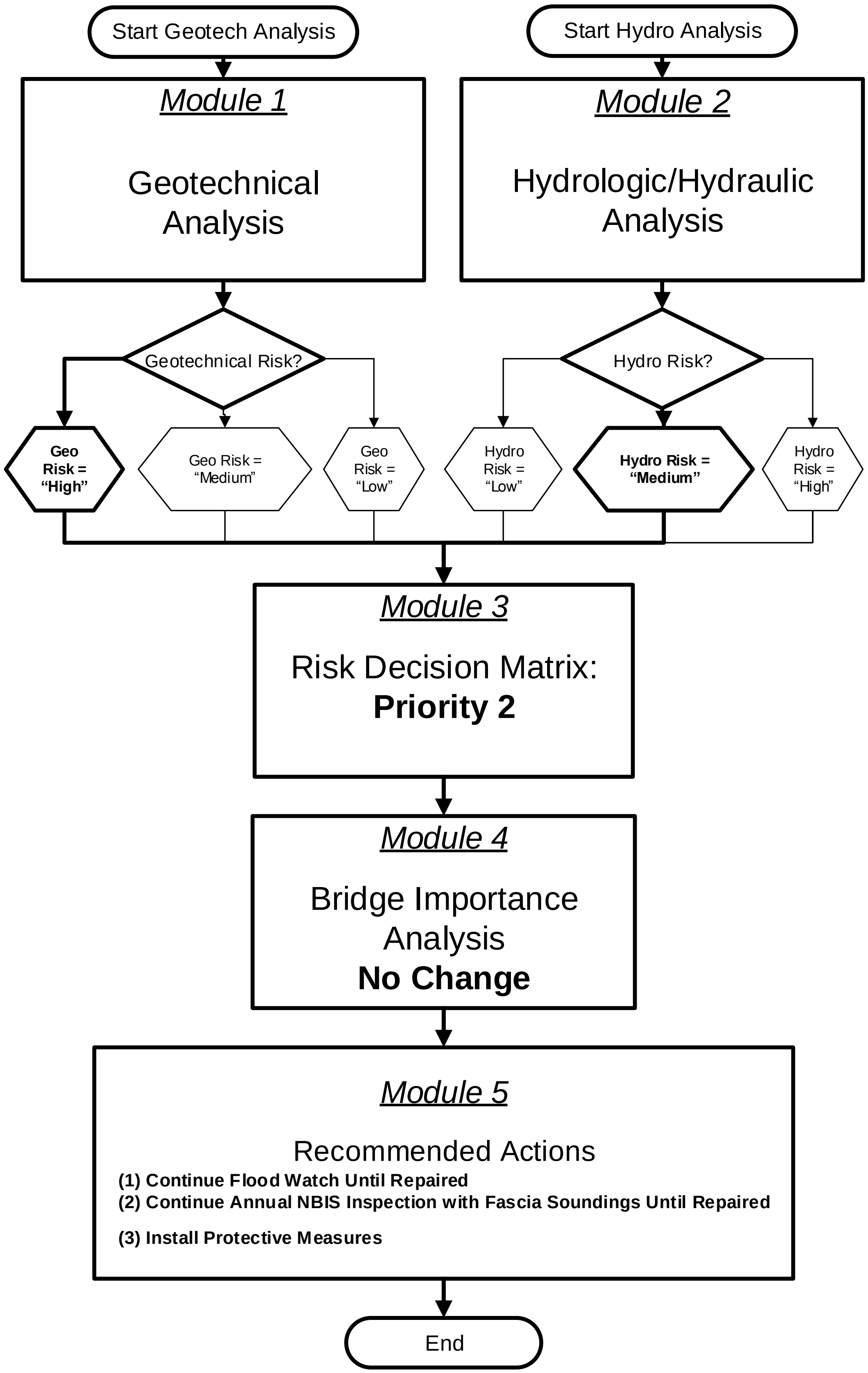
Priority Level	Matrix Risk Combinations (Geo-Hydro)	Recommended Actions (All listed actions for a given priority level must be performed)
Priority 1	High-High	(1) Continue flood watch or Install Real-time Monitoring System until repaired. (2) Continue annual NBIS inspection with fascia soundings until repaired. (3) Install Protective Measures as soon as possible (see Table 8).
Priority 2	High-Med Med-High	(1) Continue Flood Watch until repaired. (2) Continue annual NBIS inspection with fascia soundings until repaired. (3) Install Protective Measures (see Table 8).
Priority 3	Med-Med Low-High	(1) Continue annual NBIS inspection with fascia soundings until resolved. (2) Consider use of engineering judgment to designate the bridge as either Priority 2 or 4. (3) Alternatively, consider monitoring for an intermediate period (3± years), then revisit SEM Risk Analysis (See Table 8).
Priority 4	**All Others**	Bridge is recommended for removal from the Scour Critical List. Return to biannual NBIS inspection schedule. Continue M&R to control minor erosion zones and debris.

***** Note: Long term monitoring is 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 a monitoring countermeasure shall retain its scour critical code.

Note that these example results are provided for illustration purposes only. All data and risk ratings must be re-verified before undertaking any recommended actions for this bridge.

Example Problem 2: Bridge 826150

OVERVIEW OF EXAMPLE PROBLEM 2



Example Problem 2: Bridge 826150

MODULE 1 – GEOTECHNICAL ANALYSIS

Start Geotech Analysis
NJ Route 322 over Scotland Run
Monroe Township, Gloucester County, New Jersey
(826150)

↓

Step 1

Geotechnical Reconnaissance Study Results:

- Stage II:
  - Built 1970, one span, total length 27.7 ft; plain concrete vertical gravity type abutments with spread footings;
  - Bridge determined to be scour critical based on calculated scour depth according to HEC-18 formulations.
  - Channel appears laterally stable as evidenced by the channel's highly vegetated banks, the lack of steeply cut banks and unvegetated bars, and a comparison of the plan form of the channel from the original bridge drawings to the existing plan form of the channel. Long term scour is estimated at 0.48 in./yr. Field observation indicated no scour holes or significant channel degradation.
  - Two grab samples recovered from bed and grain size analyses performed.
  - Bed description: Sand with silt and clay
- USGS Surficial Geology: Swamp deposits (Qs) adjacent to Cohansey formation (Tch) with Bridgeton formation (Tbr) nearby; general texture: sand and silt with peat, muck, gravel, and clay.
- Rutgers Soil Survey: Recent alluvium and swamp (AR/Z) adjacent to alluvial material over marine deposits (AM-12/M-23); general texture: silty, clayey sand and gravel with organic material.
- USDA Web Soil Survey: Manahawkin muck (MakAt); general texture: muck with sand
- NJDOT GDMS Borings: General texture; sand with gravel.
- **Conclusion**: Consensus of bed texture is sand with gravel, silt, and clay; shallow organics. No evidence of substantial field scour.

↓

Step 2

Field Scour Investigation Results:

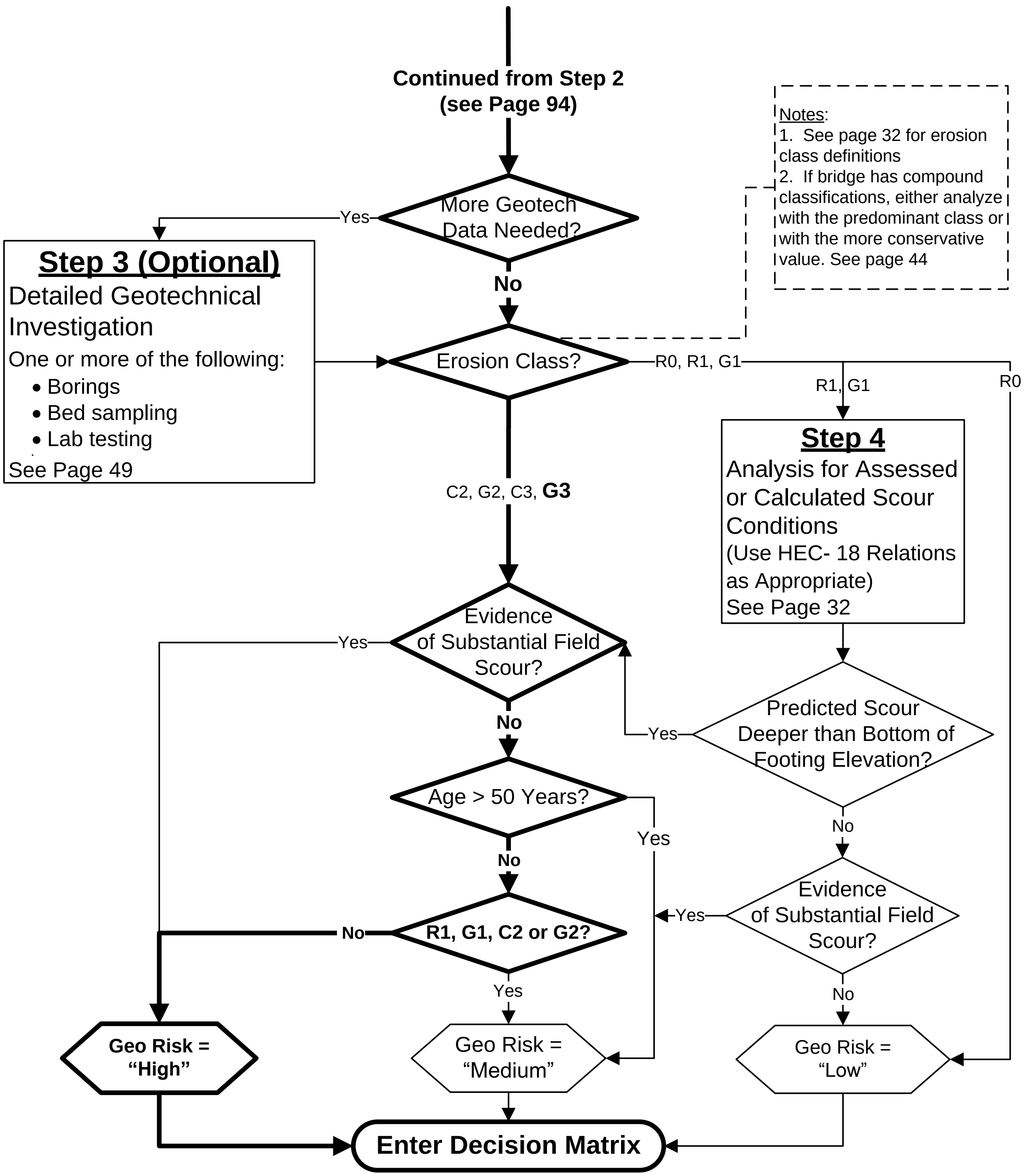
- Stream Bed Classification and Field Description: G3 – Fine to Medium Granular Soil (based on Geotechnical Reconnaissance Study results; bridge was not field inspected for this research study).
- General Channel Observations: Channel appears laterally stable as evidenced by the channel's highly vegetated banks, the lack of steeply cut banks and unvegetated bars, and a comparison of the plan form of the channel from the original bridge drawings to the existing plan form of the channel (based on Stage II field observations; bridge was not field inspected for this research study).
- Scour Observations: No evidence of substantial field scour (based on Stage II field observations; bridge was not field inspected for this research study).
- Conclusions Related to Scour: Streambed materials exhibit low erosion resistance. Bed profile beneath and in immediate vicinity of bridge is generally stable. Recommend continued maintenance and repair to control debris and minor erosion zones.

↓

Continue to More Geotech Data Needed?

Example Problem 2: Bridge 826150

MODULE 1 – GEOTECHNICAL ANALYSIS (*Continued*)



Example Problem 2: Bridge 826150

MODULE 2 – HYDROLOGIC/HYDRAULIC ANALYSIS

Start Hydro Analysis
NJ Route 322 over Scotland Run
Monroe Township, Gloucester County, New Jersey
(826150)

Step 1

Hydrologic Reconnaissance Study:

- Background:
  - Constructed in 1970
  - No stream gage located on Scotland Run. Nearest stream gage is located on Little Ease Run approximately 3 miles south of bridge (USGS 01411456). Use offstream analysis.
  - Largest flow seen (at USGS 01411456) was 627 cfs on 8/28/2011.
- Stage II Data:
  Q_{50} = 235 cfs Q_{100} = 291 cfs Q_{500}= 480 cfs
  Drainage Area = N/A
- StreamStats Results:
  Q_{50} = 291 cfs Q_{100} = 336 cfs Q_{500} = 439 cfs
  Drainage Area = 3.98 sq. mi.
- USGS Gage Data (01411456):
  Q_{50} = 527 cfs Q_{100} = 698 cfs Q_{200} = 910 cfs
  Use offstream analysis. Compute Proportion of Q_{100} seen:
  (627 cfs/698 cfs) x 100 = 89.8%
- Conclusion: Bridge has seen 89.8% of Q_{100}

Geotech Analysis

From Geotech Analysis Steps 1 & 2

Field Scour Investigation

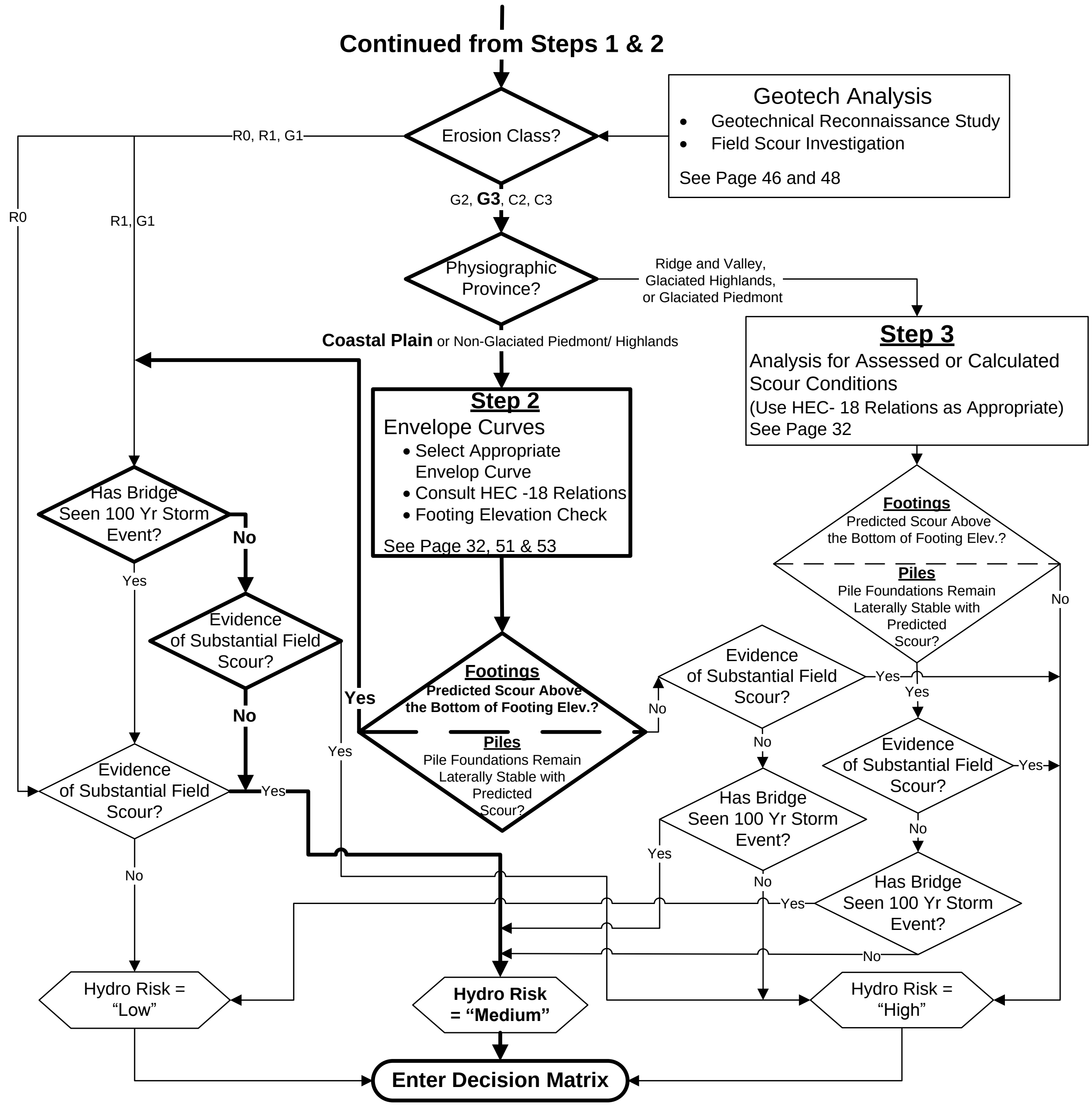
Parameters critical to Hydro Analysis:

- G3 – Fine to Medium Granular
- No evidence of substantial field scour
- Coastal Plain

Continue to Erosion Class

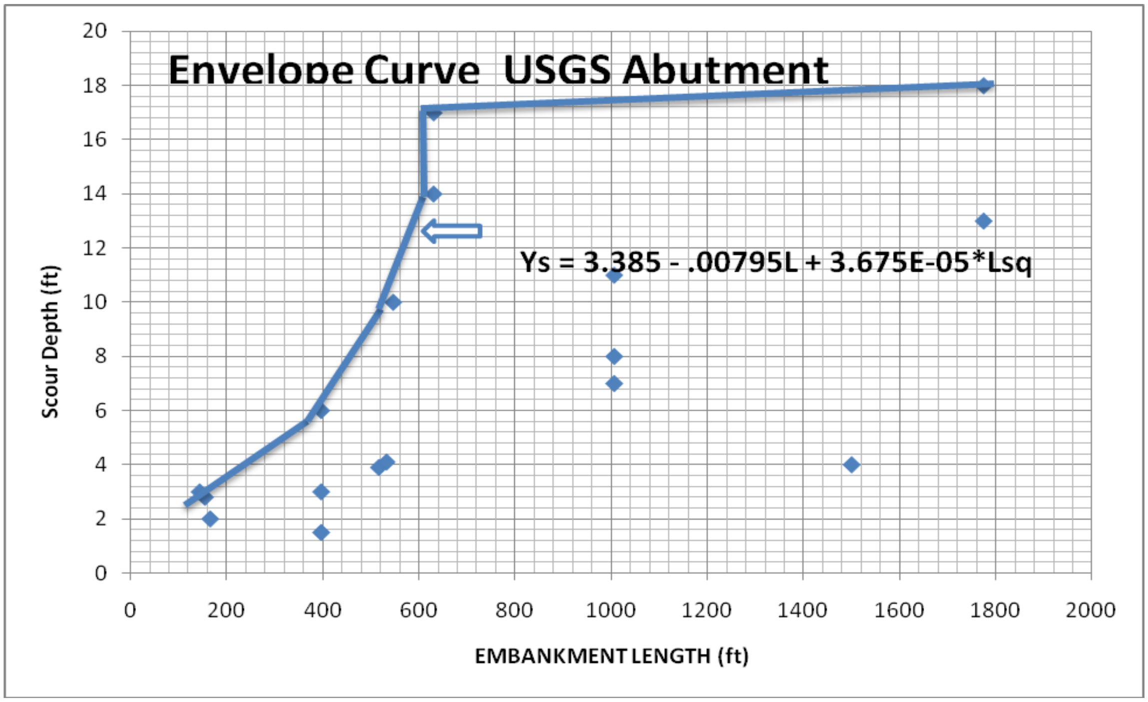
Example Problem 2: Bridge 826150

MODULE 2 – HYDROLOGIC/HYDRAULIC ANALYSIS (*Continued*)

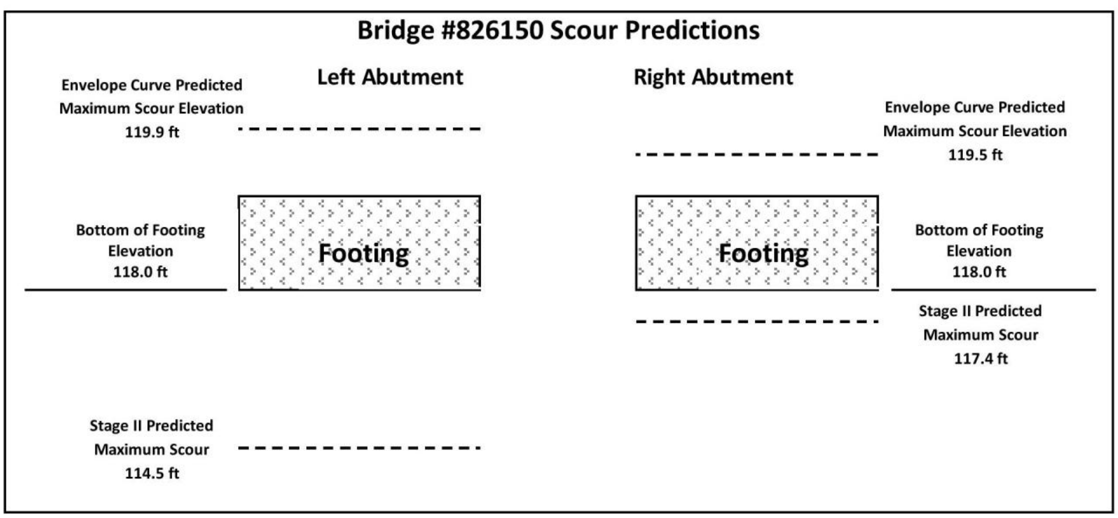


Example Problem 2: Bridge 826150

ANALYSIS OF ENVELOPE CURVES



Bridge # 826150	Left Abutment	Right Abutment
Depth of Scour from Stage II Reports	8.4	5.2
Elevation of Scour Predicted from Stage II Reports	114.5	117.4
Elevation of Bottom of Footing from Stage II Reports	118.0	118.0
Depth of Scour Predicted from Envelope Curve for Embankment Length of 81 ft.	3.0	3.1
Change in Scour Depth Predicted from Envelope Curve versus Stage II Reports	5.4	2.1
Predicted Elevation of Scour from Envelope Curve	119.9	119.5
Conclusion: 119.9>118.0 & 119.5>118.0 therefore, Maximum Scour is above left and right abutment bottom footing elevation.		



Example Problem 2: Bridge 826150

MODULE 3 – RISK DECISION MATRIX

		Geotechnical Risk		
		High	Medium	Low
Hydrologic/Hydraulic Risk	High	Scour Priority 1	Scour Priority 2	Scour Priority 3
	Medium	• Bridge 826150 Scour Priority 2	Scour Priority 3	Scour Priority 4
	Low	Scour Priority 4	Scour Priority 4	Scour Priority 4

MODULE 4 – BRIDGE IMPORTANCE MATRIX

Bridge 826150 requires analysis using the Bridge Importance Matrix as shown on the next page.

The detour length for this bridge is 5 miles. Therefore, the Detour Risk, DR, is in the “High 4+” range.

The ARF for this bridge is calculated as:

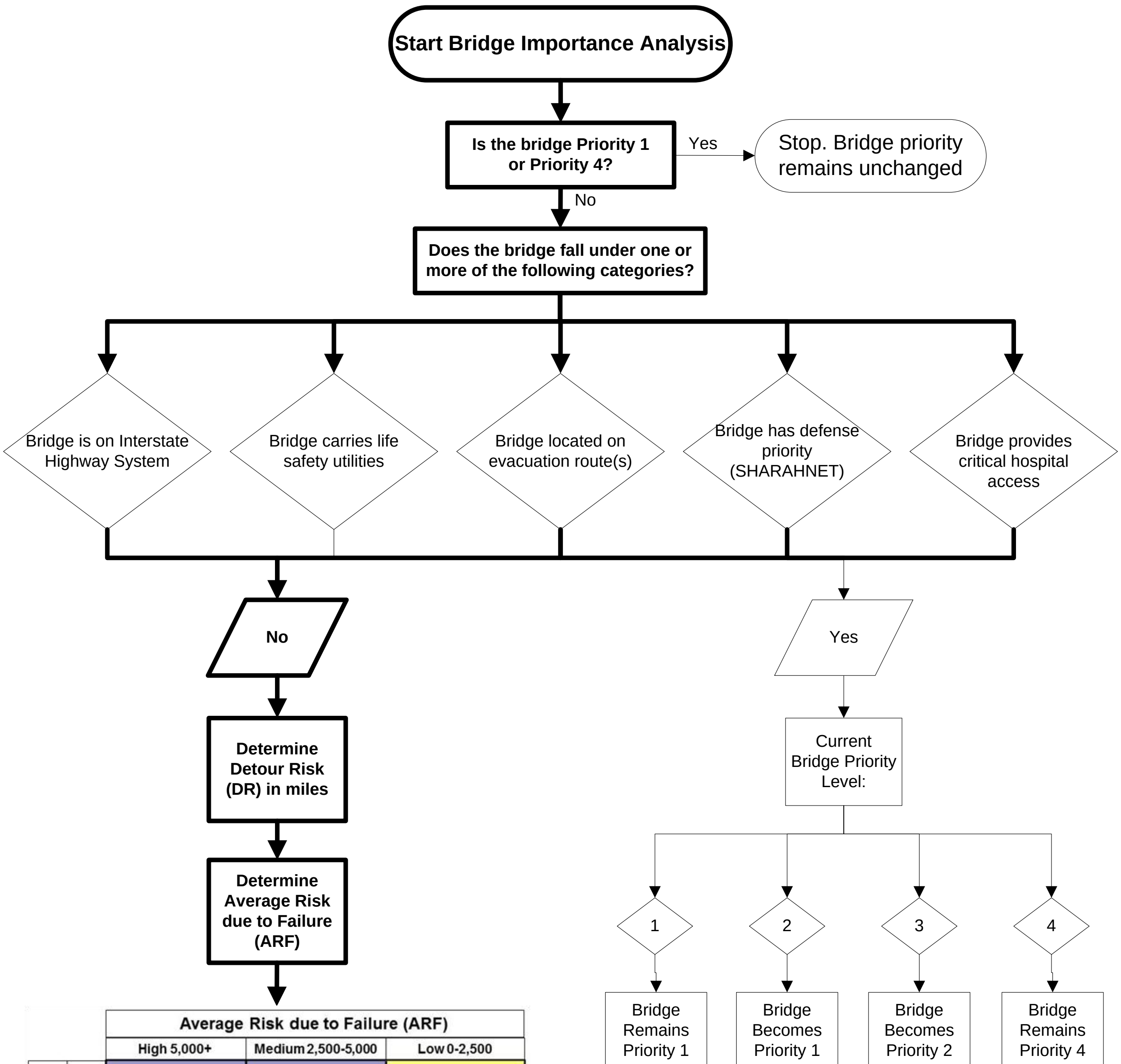
$$Average\ Risk\ due\ to\ Failure\ (ARF) = \frac{ADT\left(\frac{veh}{day}\right) * Bridge\ Length\ (ft)}{1000}$$

Where, ADT = 7670 veh/ day; Bridge Length = 28 ft.

ARF = 7670*28/1000 = 215. So, ARF is in the “Low 0- 2,500” range.

Plotting the results on the Bridge Importance Matrix, no increase in priority is required. The bridge remains as Priority 2 (see next page).

Example Problem 2: Bridge 826150



		Average Risk due to Failure (ARF)		
		High 5,000+	Medium 2,500-5,000	Low 0-2,500
Detour Risk (DR)	High 4+	Change: Priority 2 to 1 Priority 3 to 2	Change: Priority 2 to 1 Priority 3 to 2	● Bridge 826150 Do Not Increase
	Medium 2-4	Change: Priority 2 to 1 Priority 3 to 2	Do Not Increase	Do Not Increase
	Low 0-2	Change: Priority 2 to 1 Priority 3 to 2	Do Not Increase	Do Not Increase

Bridge Importance Matrix (BIM)

Example Problem 2: Bridge 826150

MODULE 5 – RECOMMENDED ACTIONS

Priority Level	**Matrix Risk Combinations** (Geo-Hydro)	**Recommended Actions** (All listed actions for a given priority level must be performed)
Priority 1	High-High	(1) Continue flood watch or Install Real-time Monitoring System until repaired. (2) Continue annual NBIS inspection with fascia soundings until repaired. (3) Install Protective Measures as soon as possible (see Table 8).
Priority 2	**High-Med** **Med-High**	(1) Continue Flood Watch until repaired. (2) Continue annual NBIS inspection with fascia soundings until repaired. (3) Install Protective Measures (see Table 8).
Priority 3	Med-Med Low-High	(1) Continue annual NBIS inspection with fascia soundings until resolved. (2) Consider use of engineering judgment to designate the bridge as either Priority 2 or 4. (3) Alternatively, consider monitoring for an intermediate period (3± years), then revisit SEM Risk Analysis (See Table 8).
Priority 4	All Others	Bridge is recommended for removal from the Scour Critical List. Return to biannual NBIS inspection schedule. Continue M&R to control minor erosion zones and debris.

***** Note: Long term monitoring is 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 a monitoring countermeasure shall retain its scour critical code.

Note that these example results are provided for illustration purposes only. All data and risk ratings must be re-verified before undertaking any recommended actions for this bridge.

REFERENCES

Annandale, G.W. (1999). "Estimation of Bridge Pier Scour Using the Erodibility Index Method." *Stream Stability and Scour at Highway Bridges: Compendium of Papers ASCE Water Resources Engineering Conferences 1991-1998,"* American Society of Civil Engineers, Reston, Va., 83-97.

Annandale, G.W. (2006). "Scour Technology," McGraw-Hill, New York.

Arneson, L.A., and Abt, S.R. (1999). "Vertical Contraction Scour at Bridges with Water Flowing Under Pressure Conditions." *Stream Stability and Scour at Highway Bridges: Compendium of Papers ASCE Water Resources Engineering Conferences 1991-1998,"* American Society of Civil Engineers, Reston, Va.

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F., and Clopper, P.E. (2012). "Evaluating Scour at Bridges (5th ed.)." HEC-18, Report No. FHWA-HIF-12-003, Federal Highway Administration., U.S. Department of Transportation, Washington D.C.

Austroads (1994). "Waterway Design – A Guide to the Hydraulic Design of Bridges, Culverts and Floodways." Austroads, Sydney, Australia.

Benedict, S.T. and Caldwell, A.W. (2006). "Development and Evaluation of Clear-Water Pier and Contraction Scour Envelope Curves in the Coastal Plain and Piedmont Provinces of South Carolina."*Scientific Investigations Report 2005-5289,* U.S. Geological Survey, Reston, Va.

Benedict, S.T., and Caldwell, A.W. (2009). "Development and Evaluation of Live-Bed Pier- and Contraction-Scour Envelope Curves in the Coastal Plain and Piedmont Provinces of South Carolina." *Scientific Investigations Report 2009-5099*,U.S. Geological Survey, Reston, Va.

Benedict, S.T., and Caldwell, A.W. (2014). "A Pier-Scour Database: 2,453 Field and Laboratory Measurements of Pier Scour Data Series Report 845. U.S. Geological Survey, Reston, VA.

Benedict, S.T., and Caldwell, A,W. (2016a). "The upper bound of pier scour in laboratory and field data", *Transportation Research Record* No. 2588, Transportation Research Board, Washington, D.C., pp. 145-153.

Benedict, S.T., and Caldwell, A.W. (2016b). "The upper bound of abutment scour in laboratory and field data," *Transportation Research Record* No. 2588, Transportation Research Board, Washington, D.C., pp. 154-162.

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.

Benedict, S.T., Feaster, T., and Caldwell, A.W. (2016). " The South Carolina Bridge-Scour Envelope Curves," Scientific Investigations Report 2016-5121. U.S. Geological Survey, Reston, VA.

Blench, T. (1969). *Mobile-bed Fluviology.* University of Alberta Press, Edmonton, Canada.

Briaud, J.L., Chen, H.C., Chang, K.A., Oh, S.J., Chen, S., Wang, J., Li, Y., Kwak, K., Nartjaho, P., Gudaralli, R., Wei, W., Pergu, S., Cao, Y.W., and Ting, F. (2011). "The SRICOS – EFA Method" Summary Report, Texas A&M University.

Briaud, J.-L., Chen, H.-C., Li, Y., and Wang, and Nurtjahyo, P. J. (2003). “Complex Pier Scour and Contraction Scour in Cohesive Soils.” *NCHRP Report 24-15*, Transportation Research Board, National Research Council, Washington, D.C.

Briaud, J.-L., Govindasamy, A.V., Kim, D., Gardoni, P., Olivera, F., Chen, H.-C., Mathewson, C., and Elsbury, K. (2009). “Simplified Method for Estimating Scour at Bridges.” *Report FHWA/TX-09/0-5505-1* Texas Transportation Institute, Texas A&M University, Civil Engineering, and Texas Dept. of Transportation, College Station, Texas. <http://tti.tamu.edu/documents/0-5505-1.pdf>

Briaud, J.-L., Ting, F.C.K., Chen, H.-C., Gudavalli, R., Perugu, S., Wei, G. (1999), “SRICOS: Prediction of Scour Rate in Cohesive soils at Bridge Piers,” *ASCE Journal of Geotechnical & Geoenvironmental Engineering*, 125(4), 237-246.

Briaud, J.-L., Ting, F.C.K., Chen, H.-C., Gudavalli, R., Kwak, K., Philogene, B., Han, S.W., Perugu, S., Wei, G., Nurtjahyo, P., Cao, Y., Li, Y., (1999). "SRICOS Prediction of Scour Rate at Bridge Piers," *Report 2937-F*, Texas Depart. of Transportation, Texas A&M University, Civil Engineering, College Station, Texas.

Chang, F. and S.R. Davis. (1999). "Maryland SHA Procedure for Estimating Scour at Bridge Abutments, Part I – Live Bed Scour," ASCE Compendium, Stream Stability and Scour at Highway Bridges, Richardson and Lagasse (eds.), Reston, Va.

Chang, F. and S.R. Davis. (1999). "The Maryland State Highway Administration ABSCOUR Program," Maryland SHA.

Cinotto, P.J., and White, K.E. (2000). “Procedures for Scour Assessments at Bridges in Pennsylvania.” *Open-File Report 00-64,* U.S. Geological Survey, Reston, Va.

Connecticut Department of Transportation (2000). “ConnDOT Drainage Manual, Appendix B – Amended Local Abutment Scour Equations for Connecticut.” ConnDOT, Newington, Conn.

Ettema, R., Constantinescu, G, and Melville, B.W. (2011). “Evaluation of Bridge Scour Research: Pier Scour Processes and Predictions,” NCHRP Web Only Document 175, Final Report for NCHRP Project 24-27(01), Transportation Research Board of the National Academies, Washington D.C. <http://www.ct.gov/dot/lib/dot/documents/ddrainage/9.B.pdf>

Ettema, R., Nakato, T., and Muste, M. (2011) "Estimation of Scour Depth at Bridge Abutments," NCHRP Project 24-20, Final Report, Transportation Research Board, National Academy of Science, Washington, D.C.

Federal Highway Administration (2009). “Stream Instability, Bridge Scour, and Countermeasures, A Field Guide for Bridge Inspectors” National Highway Institute, FHWA-NHI-08-106.

Federal Highway Administration (1991). “Memorandum: Scourability of Rock Formations,” issued by Chief, Bridge Division, FHWA, Washington, D.C.

Florida Department of Transportation, (2011). "Bridge Scour Manual," Tallahassee, FL.

Forest Service, Region 1, U.S. Department of Agriculture (1998). “Bridge Scour Evaluation: Screening, Analysis, & Countermeasures.” *Report No. 9877 1207—SDTDC,* San Dimas Technology and Development Center, San Dimas, Ca.

Froehlich, D.C. (1989). "Abutment Scour Prediction." *Transportation Research Board Presentation*, Washington, D.C.

Google Earth (Version 6.0.3) [Software] (2009). Google Inc., Mountain View, CA. <http://www.google.com/earth/download/ge/>

Guo, J., Suaznabar, O., Shan, H., Xie, Z., Shen, J., and Kerenyi, K. (2012). "Pier Scour in Clear-Water Conditions with Nonuniform Bed Materials," Federal Highway Administration, Report No. FHWA-HRT-12-022.

Hodgkins, G., and Lombard, P. (2002). “Observed and Predicted Pier Scour in Maine.” *Water-Resources Investigations Report 02-4229*, U. S. Geological Survey, Reston, Va. <http://me.water.usgs.gov/reports/wrir02-4229.pdf>

Holmes, P.S. (1974). “Analysis and Prediction of Scour at Railway Bridges in New Zealand.” *New Zealand Engineering*, November, 313-320.

Illinois Department of Transportation, Bureau of Bridges and Structures. (2009), “Bridge Manual.” Springfield, Ill. <http://www.dot.state.il.us/bridges/brmanuals.html>

Jain, S.C., and Fischer, R.E. (1979). "Scour Around Bridge Piers at High Froude Numbers*." Report No. FHWA-RD-79-104*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Johnson, P.A., and Torrico, E.F. (1994). "Scour Around Wide Piers in Shallow Water." *Transportation Research Board Record 1471,*Transportation Research Board, Washington, D.C.

Jones, J.S. (1983). "Comparison of Prediction Equations for Bridge Pier and Abutment Scour." Transportation Research Record 950, Second Bridge Engineering Conference, Vol. 2, Transportation Research Board, Washington, D.C.

Jones, J.S. and Sheppard, D.M. (2000). "Local Scour at Complex Pier Geometries," Proceedings of the ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management, July 30 - August 2, Minneapolis, MN.

Keaton, J.R., Mishra, S.K., and Clopper, P.E. (2011). "Scour at Bridge Foundations on Rock," Final Report, NCHRP Project 24-29, Transportation Research Board, National Academy of Science, Washington, D.C.

Lagasse, P.F., Zevenbergen, L.W., Spitz, W.J. and Arneson, L.A. (2012). "Stream Stability at Highway Structures” (4th ed.)." HEC-20, Report No. FHWA-HIF-12-004, Federal Highway Administration., U.S. Department of Transportation, Washington D.C

Landers, M.N., Mueller, D.S., and Richardson, E.V. (1999). "U.S. Geological Survey Field Measurements of Pier Scour." *Stream Stability and Scour at Bridges:*

Compendium of Papers ASCE Water Resources Engineering Conferences 1991-1998,” American Society of Civil Engineers, Reston, Va.,.

Laursen, E.M. (1960). "Scour at Bridge Crossings," Journal Hydraulic Division, American Society of Civil Engineers, Vol. 86, No. HY 2.

Laursen, E.M. (1963). "An Analysis of Relief Bridge Scour," Journal Hydraulic Division, American Society of Civil Engineers, Vol. 89, No. HY3.

Laursen, E.M. (1980). "Predicting Scour at Bridge Piers and Abutments." *General Report No. 3*, Arizona Department of Transportation, Phoenix, Ariz.

Lacey, G. (1930). “Stable Channels in Alluvium.” *Minutes of the Proc., Institution of Civil Engineers,* London, Great Britain, 229, 259-292.

Lee, K.G., and Hedgecock, T.S. (2008). “Clear-Water Contraction Scour at Selected Bridge Sites in the Black Prairie Belt of the Coastal Plain in Alabama, 2006.” *Scientific Investigations Report 2007–5260*, U.S. Geological Survey, Reston, Va. <*http://pubs.usgs.gov/sir/2007/5260/*>.

Liu, H.K., Chang, F.M., and Skinner, M.M. (1961). "Effect of Bridge Constriction on Scour and Backwater." Department of Civil Engineering, Colorado State University, Fort Collins, Colo.

Lombard, P.J., and Hodgkins, G.A. (2008). “Comparison of Observed and Predicted Abutment Scour at Selected Bridges in Maine.” *Scientific Investigations Report 2008-5099*, U.S. Geological Survey, Reston, Va.

Maryland State Highway Administration (2007). “ABSCOUR Users Manual.” (Updated from 1999 version: Chang, F., and. Davis, S.R. (1999). "The Maryland State Highway Administration ABSCOUR Program.") Maryland SHA, Baltimore, Md. <http://www.gishydro.umd.edu/sha_sept07/CH%2011%20SCOUR/3%20CH%2011%20APP%20A%20PART%20II.pdf>

Melville, B.W., and Coleman, S.E. (2000). *Bridge Scour*. Water Resource Publications, LLC., Highlands Ranch, Colo.

Melville, B.W. and Dongol, D.M. (1992). "Bridge Pier Scour with Debris Accumulation." *Journal of Hydraulic Engineering*., ASCE, 118(9).

Melville, B.W. (1992). "Local Scour at Bridge Abutments." *Journal of Hydraulic Engineering*, 118(4),.

Melville, B.W. (1997). "Pier and Abutment Scour – An Integrated Approach.” *Journal of Hydraulic Engineering*, 123(2), 125-136.

Melville, B.W. and Sutherland, A.J. (1988). "Design Method for Local Scour at Bridge Piers." *Journal of Hydraulic Engineering*, 114(10).

Mueller, D.S. (1996). "Local Scour at Bridge Piers in Nonuniform Sediment Under Dynamic Conditions," dissertation, presented to Colorado State University at Fort Collins, CO, in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Mueller, D.S. and J.S. Jones (1999). "Evaluation of Recent Field and Laboratory Research on Scour at Bridge Piers in Coarse Bed Materials." Stream Stability and Scour at Highway Bridges: Compendium of Papers ASCE Water Resources Engineering Conferences 1991-1998," ASCE, Reston, Va.

Neill, C.R. (1973). *Guide to Bridge Hydraulics.* Roads and Transportation Assoc. of Canada, University of Toronto Press, Toronto, Canada.

Neill, C.R. (1987). "Bridge Hydraulics – an Update Report." Roads and Transportation Assoc. of Canada, Ottawa, Canada.

New Jersey Department of Environmental Protection (2008). "Draft Technical Manual, Flood Hazard Area Control Act Rules." Division of Land Use Management, N.J.A.C. 7:13, Trenton, NJ.

New Jersey Department of Transportation (2006). "Bridge Scour Evaluation Program Plan of Action Report for Stage II In-Depth Scour Evaluation of State Bridges." NJDOT (prepared by Earth Tech), Ewing, NJ.

New Jersey Department of Transportation (2009). "Design Manual for Bridges and Structures." 5th Ed. NJDOT, Ewing, NJ.

New Jersey Geological Survey (2011). "Physiographic Provinces of New Jersey." [map] *Digital Geodata Series (DGS) 02-7,* New Jersey Department of Environmental Protection, Trenton, NJ. <http://www.nj.gov/dep/njgs/geodata/dgs02-7.htm>

New Jersey Institute of Technology (2009). *Survey of Scour Practice*, NJIT, Newark, NJ.

"NJDOT Geotechnical Database Management System (GDMS)." New Jersey Department of Transportation, Ewing, NJ. [boring logs and plans] <https://wwwnet1.state.nj.us/DOT/geotechnical/GDMS/MapFrames.aspx>.

Pennsylvania Department of Transportation. (2000), "Design Manual, Part 4, Vol. 1," *PDT – Pub. No 15M*, Harrisburg, Pa. <ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%2015M.pdf>

Raudkivi, A.J. (1986). "Functional Trends of Scour at Bridge Piers." *Journal of Hydraulic Engineering*, ASCE, 112 (1).

Richardson, E.V. and Abed, L. (1993). "Topwidth of Pier Scour Holes in Free and Pressure Flow," ASCE Hydraulic Engineering, Proc. 1993 National Conference, San Francisco, CA, August.

Richardson, E.V. and Davis, S.R. (2001). "Evaluating Scour at Bridges (4th ed.)." *HEC-18*, *Report No. FHWA NHI 01-001,* Federal Highway Administration., U.S. Department of Transportation, Washington, D.C.

Richardson, E.V., Simons, D.B., and Lagasse, P.F. (2001). "River Engineering for Highway Encroachments - Highways in the River Environment." *Report No. FHWA NHI 01-004, Hydraulic Series No. 6*, Federal Highway Administration, Washington, D.C.

Richardson, J.R., and Richardson, E.V. (1994). "Practical Method for Scour Prediction at Bridge Piers," *Proc., ASCE Hydraulic Engineering, 1994 National Conference*, ASCE, Reston, Va.

Rutgers University (1951). “Rutgers University Engineering Soil Survey of New Jersey.” *Report No. 2, Essex County*, New Brunswick, N.J.

Also available: Passaic County (No. 3), Bergen and Hudson Counties (No. 4), Union County (No. 5), Hunterdon County (No. 6), Somerset County (No. 7), Ocean County(No. 8), Morris County (No. 9), Middlesex County (No. 10), Sussex County (No. 11), Mercer County (No. 12), Warren County (No. 13), Salem County (No. 14), Cape May County (No. 15), Gloucester County (No. 16), Camden County (No. 17), Atlantic County (No. 18), Monmouth County (No. 19), Burlington County (No. 20), and Cumberland County (No. 21)

Salim, M., and Jones, J.S. (1995). "Effects of Exposed Pile Foundations on Local Pier Scour." *Proc., ASCE Water Resources Engineering Conference,* ASCE, Reston, Va.

South Carolina Department of Transportation (2009). “Requirements for Hydraulic Design Studies.” SCDOT, Columbia, S.C.

Schuring, J. R., Dresnack R., Golub E., Khan M.A., Young M.R., Dunne R., and Aboobaker N. (2010). “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.

Sheppard, M., Demir, H. and Melville, B.W. (2011). “Scour at Wide Piers and Long Skewed Piers,” NCHRP Report 682, Final Report for NCHRP Project 24-32, Transportation Research Board of the National Academies, Washington D.C.

Sturm, T.W. (1999). "Abutment Scour in Compound Channels." Stream Stability and Scour at Highway Bridges, ASCE Compendium: Compendium of Papers ASCE Water Resources Engineering Conferences 1991-1998,” American Society of Civil Engineers, Reston, Va.

Sturm, T.W. (1999). “Abutment Scour Studies for Compound Channels,” U.S. Department of Transportation, Federal Highway Administration, September.

Sturm, T.W. (2004). “Enhanced Abutment Scour Studies for Compound Channels.” *Report FHWA-RD-99-156*, U.S. Department of Transportation, Federal Highway Administration, McLean, Va.

Tague, N. (2004). *The Quality Toolbox, Second Edition*, ASQ Quality Press, Milwaukee, Wis.

Texas Department of Transportation (2006). “Geotechnical Manual.” Austin, Texas.

“USDA Web Soil Survey.” National Resources Conservation Services, U.S. Department of Agriculture, Washington, D.C. <http://www.nrcs.usda.gov/>.

U. S. Geological Survey: Drake Jr., A.A., Volkert, R.A., Monteverde, D.H., Herman, G.G., Houghton, H.F., Parker, R.A., and Dalton, R.F. (1996). “Bedrock Geologic Map of Northern New Jersey (2 Sheets)” [map]. 1:100,000. *Miscellaneous Investigations Series Map I-2540-A,* USGS (in cooperation with NJGS),Reston, Va. (Maps for various New Jersey Quadrangles are also available.)

U. S. Geological Survey: Owens, J.P., Sugarman, P.J., Sohl, N.F., Parker, R.A., Houghton, H.F., Volkert, R.A., Drake Jr., A.A., and Orndorff, R.C. (1998). “Bedrock Geologic Map of Central and Southern New Jersey (4 Sheets)” [map]. 1:100,000. *Miscellaneous Investigations Series Map I-2540-B,* USGS (in cooperation with NJGS),Reston, Va. (Maps for various New Jersey Quadrangles are also available.)

U. S. Geological Survey: Stone, B.D., Stanford, S. D., and Witte, R.W. (2002). “Surficial Geologic Map of Northern New Jersey (3 Sheets)” [map]. 1:100,000. *Miscellaneous Investigations Series Map I-2540-C,* USGS (in cooperation with NJGS),Reston, Va. (Maps for various New Jersey Quadrangles are also available.)

U. S. Geological Survey: Newell, W.L., Powars, D.S., Woens, J.P., Stanford, S.D., and Stone, B.D. (2000). “Surficial Geologic Map of Central and Southern New Jersey (3 Sheets)” [map]. 1:100,000. *Miscellaneous Investigations Series Map I-2540-D,* USGS (in cooperation with NJGS),Reston, Va. (Maps for various New Jersey Quadrangles are also available.)

U.S. Department of Transportation (1988). "Scour at Bridges." *Technical Advisory T5140.20,* Federal Highway Administration, Washington, D.C.

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.

“WaterWatch Map of Real-Time Streamflow Compared to Historical Streamflow for the Day of the Year (New Jersey).” (2011). U.S. Geological Survey. <http://waterwatch.usgs.gov/new/?m=real&r=nj&w=real%2Cmap>.

Watson, K.M., and Schopp, R.D. (2009). “Methodology for Estimation of Flood Magnitude and Frequency for New Jersey Streams.” *Scientific Investigations Report 2009–5167*, U.S. Geological Survey, Reston, Va.

Stage II Reports

During the this research study, the Stage II In-Depth Scour Evaluation Reports for 165 of the State’s scour critical bridges were reviewed and analyzed. These are currently available at the offices of AECOM in Piscataway, NJ.

Listing of Stage II In-Depth Scour Evaluation Bridge Scour Evaluation Reports:

Bridge Number	Bridge Number	Bridge Number	Bridge Number	Bridge Number	Bridge Number	Bridge Number	Bridge Number	Bridge Number	Bridge Number
118150	317152	606150	826150	1222150	1407153	1601157	1807155	1911159	2106164
118152	319152	609151	1005153	1227159	1407156	1601160	1809150	1912158	2107154
118153	324152	609152	1005162	1303155	1409154	1604150	1809153	1912160	2107155
119151	324153	709150	1005163	1304151	1410159	1605153	1809158	1922150	2107156
119156	324155	711150	1006151	1304156	1411152	1605156	1810153	1922151	2108162
201151	324156	716156	1009150	1308154	1413155	1605158	1810155	1923150	2111151
206166	324160	719151	1013152	1315157	1416152	1605162	1810158	2003157	2111155
206181	324162	722157	1015157	1320152	1417156	1605167	1810164	2003161	2113160

206189	326152	722158	1016156	1321150	1417157	1605175	1810165	2003162	2117157
216150	326153	807152	1016157	1401156	1417159	1612154	1903152	2004151	2117159
216157	405153	808151	1102150	1402150	1418154	1619151	1903153	2006151	2117160
218161	408160	810150	1105152	1403150	1424150	1703152	1904152	2006152	2117160
218162	424151	815152	1110158	1404155	1502153	1705150	1904153	2012150	
220157	509150	817150	1122150	1404158	1502154	1716151	1905151	2102154	
225166	510152	817151	1123152	1404159	1502157	1801153	1907152	2103152	
316150	601150	818151	1123153	1405156	1516151	1801154	1907157	2103153	
317150	601151	825150	1218158	1407152	1516152	1803156	1911151	2105164	