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Factors Affecting Stream and Foundation Stability at Existing Bridges in New Jersey

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ABSTRACT

Scour analysis procedures for existing bridges as adopted by FHWA (HEC-18) require extensive data collection both in the field and in the design office. Data collection methods are discussed here to serve as guidelines. For 'unknown foundations,' when no as-built drawings are available, test borings are found necessary, in order to determine any presence of rock, rock elevations and the foundation depth.

The factors, which affect stream stability, include the location of the bridge either close to a river bend or at a skew angle to the direction of flow, aggradation, longitudinal slope and coefficient of roughness. The factors which affect foundation stability include the use of shallow foundations, placing the footing above computed scour depth or deficiencies such as absence of river training measures, lack of foundation armoring.

A methodology for scour study is summarized here. In addition to hydrologic studies applicable to New Jersey rivers (Stankowski method), hydraulic studies (applying HEC-RAS software) and detailed scour analysis (using Excel Spreadsheets for HEC-18 formulae) were performed. The procedures developed represent the current state of art in USA and serve as practical basis for a similar scour study.

Scour studies of two typical bridges show that the S.I. & A. Inventory Codings for Phase I need to be revised. The first bridge can be 'salvaged' by extensive foundation repairs, while the second bridge would need replacement (Figures 1 and 2).

INTRODUCTION

Recently, the New Jersey Department of Transportation completed an in-depth study to evaluate the condition of over 200 bridges, whose foundations are subjected to continued undermining from floods. STV Incorporated were assigned the task of performing the in-depth (Stage II, Phase 3) scour studies for eleven bridges. Two of the bridges (Figures 3 and 4) are selected here as typical cases to represent the eleven 'scour critical' bridges, for the purpose of a unified analytical approach and for countermeasures design. The bridges are located in the same watershed in Hunterdon County.

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Stream stability and bridge scour have been addressed as a design criteria in the AASHTO LRFD Bridge Design Specifications 1998, Section 2.6 (Ref. 1). Section 2.6.4.4.2 requires "the design flood shall be more severe of the 100-year events or from an overtopping flood of lesser recurrence interval. For check flood for scour, the stability of bridge foundation shall be investigated for scour conditions resulting from a designated flood not to exceed the 500-year event." A flow diagram (Figure 5) developed by STV shows the detailed procedure for evaluating scour. Data Collection procedures based on office and field surveys are summarized in Appendix A.

DESCRIPTION OF THE CROSSINGS

Both the bridges are of single span and are located in Tewksbury Township, Hunterdon County. The Guinea Hollow Road Bridge is located in the watershed of the North Branch of the Rockaway Creek (See Figure 3). The bridge is 1360 feet upstream from the confluence with Rockaway Creek. The waterway is oriented at a 20 degree angle to the bridge. There were no available as-built drawings to verify the footing sizes and depths.

The Water Street Bridge is located in the watershed of the Tributary to North Branch of the Rockaway Creek (See Figure 4). It was constructed originally in 1938 and re-constructed in 1948. The bridge is 700 feet upstream from the confluence with the North Branch of Rockaway Creek. The waterway is oriented at 45-degree angle to the bridge.

INVESTIGATING CONDITIONS OF UNKNOWN FOUNDATIONS

FHWA published recommendations to investigate unknown bridge foundations (Ref.6),"About 104,000 bridges in National Bridge Inventory have unknown foundations". In terms of the type and/or depth. These unknown bridge foundations pose a significant problem to state DOT's from a scour safety evaluation perspective. Because of the risk of scour undermining bridge foundations and the threat to public safety … the foundation type and depth information is needed to perform an accurate scour evaluation of each bridge." Foundation details and as-built plans were not available for these existing bridges. HEC 18, Appendix K (Ref. 3) describes detailed procedures. The suitability of alternate methods (Refs. 6 and 7) are discussed here:

1. **Direct methods such as probes, augers or rotary drilling adjacent to footings**: Probes which were carried out underwater to locate the top of existing footings did not give accurate information. Digging test pits was not used due to the danger of undermining existing footings.

2. **Nondestructive tests:** Ground penetrating radar or acoustical emission techniques were considered. Due to the unknown type of soil and stone masonry supported on stone sub-strata, this technique could not determine accurate depth of footings.

3. **Drilling test borings:** Drilling through the heel of abutment footing, obtaining bore hole logs and analyzing them was found to be a reliable method and provided detailed foundation and rock information. The method and cost was approved by NJDOT. The test boring provided information on footing depth, elevation and quality of rock located under the footing.

HYDRAULIC AND GEOMORPHIC FACTORS AFFECTING SCOUR

ASCE Compendium (Ref.2) lists several scour studies based upon a variety of causes. Hydraulic and geomorphic factors appear to be the most important and are discussed.

- **Upstream Features:** Guinea Hollow Road bridge is located downstream of a small dam and a footbridge. The presence of dam has helped to reduce high velocities downstream at the bridge location during flood events. However, the Water Street Bridge is located in a heavily forested area. The flow velocities are average.

- **Direction of River Flow:** Both the bridges are located on a well-developed bend and have sharp skew angles which cause the shifting of thalweg and non-uniform velocity distribution leading to scour of the bed and bank at the outside of the bend, and deposition at the inside of the bend.

- **Existing River Training Measures:** For both bridges, there is no evidence of dyke or spurs constructed along the outer bend to reduce the effects of long term scour. Hence the scour has remained unmitigated throughout the long life of the structure.

- **Longitudinal Slope:** The longitudinal slopes of the channel vary between 3% and 4% upstream for Guinea Hollow Road Bridge and between 2.4% and 3% downstream for Water Street Bridge. The slopes are not steep and as per Manning's equation for normal depth in an open channel, critical or supercritical velocities are not affected.

- **Aggradation:** The channel beds are littered with stones and small size boulders providing partial armoring of the bed against scour holes. Coefficient of roughness is affected. Part of the Water St. Bridge opening is clogged by medium size stones deposited by earlier floods, thereby reducing effective channel area and increasing velocity of flow under the bridge

- **Type of Stream Bed:** Soil samples tested in the laboratory have shown the Guinea Hollow Road bridge stream bed as granular in nature, with some large stones mixed with gravel and a substantial fraction of sand. Median size of aggregate (D_{50}) varies between 1 to 5 mm. Gravel layer has an armoring effect and leads to low degradation.

For Water Street bridge medium sand and traces of fine sand mixed with gravel are found with the median sizes of the aggregate (D_{50}) varying between 1 to 2 mm. The degradation of streambed or banks has been significant.

- **Bridge Skew**
  For Guinea Hollow Bridge the skew of 20 degrees in plan has resulted from a bend. The meander may continue to move laterally outward and downstream, eroding the left bank and increasing scour depth in the future.
  For Water St. Bridge the channel makes an abrupt change in direction upstream of the bridge, creating an increase in water velocity. The bridge skew of 45 degrees has resulted from bend or river meander. The meander may continue to move laterally outward and downstream, eroding the Right Bank and increasing scour in the future.

- **Depth below riverbed to top of Footings:** Test borings have shown the depths of bottom of spread footings as 'shallow' making them scour critical.

SCOUR DEPTH SUMMARY

Contraction, local and total scour depths for check flood500 years are plotted in Figures 6 and 7. Modified Laursen's equation, Froehlich's equation and Hire's equation are summarized in Appendix B.

Flood Discharge Frequency	Long Term Scour ft.	Contraction Scour ft.	Local Scour ft.	Total Scour ft.	Net Scour to bedrock ft.
South Abutment, Guinea Hollow Road Bridge -50 Year	0	4.30	14.95	19.25	7.0
100 Year	0	4.59	15.33	19.92	7.0
500 Year	0	5.49	16.07	21.56	7.0
East Abutment, Water Street Bridge - 50 Year	0	6.99	16.18	23.18	1.2
100 Year	0	7.38	17.67	25.05	1.2
500 Year	0	6.98	12.65	19.62	1.2

Notes:

1. The bottom of footing elevation has been determined by test boring.
2. Elevations referenced to National Geodetic Vertical Datum (NGVD) 1929.
3. Scour below the bedrock (granite) was neglected for 50, 100 and 500 year floods since elevation of igneous rock controls.
4. For Water Street Bridge due to levee at the banks under 500 year flood, the water overbanks. Both the wetted perimeter and roughness coefficient increase. Hence lower velocity and scour depth occurs.

5. For both bridges, the computed potential total scour is substantial for 50 and 100 year floods and scour depth exceeds the depth of footing, making the bridge scour-critical.

CHECKING PHASE I SCOUR CRITICAL DETERMINATION

Preliminary NJDOT (Stage I) study has shown that both the bridges are scour critical. Present STV (Stage II) study based on applicable methods and formulae (Figures 6 and 7) indicate that the bridge is scour critical and confirm the earlier findings:

Guinea Hollow Road Bridge

- Evidence of undermining at both abutment footings
- Evidence of poor quality masonry walls with missing mortar in joints
- Evidence of large size scour holes close to the abutments: Two large scour holes of over 3 feet depth are located in the bridge area is shown in Fig. 3 indicating severe scour. The size of scour hole is likely to increase in the future and undermine the south abutment footing.

Water Street Bridge

- Evidence of undermining at the east abutment footing
- Evidence of large size scour holes close to the abutments

Further, test boring at east abutment has shown that there is good quality rock within 2 feet below bottom of footing, thereby reducing effective scour depth considerably. There appears to be a deficiency in the original design, of placing the footing at a shallow depth. The east abutment footing has become fully exposed; thereby making any remedial measures expensive or ineffective.

RECOMMENDED BRIDGE INVENTORY CODINGS

Codings serve as the indicator of structural health of the bridge. Based upon the in-depth (Stage II) bridge scour evaluation, earlier Stage I, SI&A Codings (Federal Coding Guides, Ref. 5) for this structure may be revised as follows:

Coding Guides	Description	Stage I Coding- Guinea Hollow Road Bridge	Stage II Coding- Guinea Hollow Road Bridge	Stage I Coding- Water St. Bridge	Stage II Coding- Water St. Bridge
Item 61	Channel/Channel Protection (Stream Stability, Channel Condition, Slope Protection)	6	6	7	7
Item 71	Waterway Adequacy (Overtopping Flood frequency	9	9	5	5
Item 113	Scour Critical Bridges (Abutments are rated as unstable due to scour)	4	3*	7	2**

* Stage I SI&A rating is revised to 3 based on scour analysis.
** Stage I SI&A rating is revised to category 2, based on scour analysis.

Computed scour calculations for Stage II, Phase 3 show that the bridges are scour critical and scour depth is below the bottom of spread footing base. The conditions of the bridges are considerably worse than estimated in Stage I and remedial measures need to be implemented on a priority basis.

COUNTERMEASURE EVALUATION

In order to preserve the long term structural integrity of the bridge from damage by scour the following remedial measures, in line with HEC-23 (Ref. 4) countermeasures matrix, need to be implemented:

Structural countermeasures: Cast-in-place concrete apron (Fig. 1) serves as a good example.

Hydraulic (Armoring) countermeasures: Common materials used for revetment are riprap, gabion mattress, concrete bags or toskanes. Timber or Steel sheeting or concrete paving, to armor the exposed faces of the existing footings was investigated to select the most cost-effective method. Due to confined space under the bridge, driving of sheeting would not be practical. Hence, riprap adjacent to abutment footing and level with riverbed elevation was adopted (Eq. 8.1, Page 8.3, Ref. 4). Also, countermeasures directive in HEC-18 (Appendix J, Page J.3, Ref. 3) was followed.
For Water Street Bridge, bottom of east abutment footing is at the same level as the riverbed. Hence any riprap will be washed away during the flood and will not act as an armor. Placing grout bags on geotextile Class C layers, adjacent to East abutment appears to be a cost-effective method (Fig. 2).

Environmental concerns: Stream encroachment permit and a General Permit # 10 from NJDEP are required to install armoring. Hence sizes of revetments need to be controlled and construction method should prevent river pollution.

Monitoring: Visual inspection on a regular two-year cycle and flood watch needs to be carried out. Monitoring efforts need to be increased during high flow events.

Recommendations

For Guinea Hollow Road Bridge, placing of riprap adjacent to the apron on north and south abutments appears to be the most cost-effective method. Conceptual sketches, showing riprap depth and extent of riprap at south abutment, are shown in Figure 1. Cost of countermeasures are estimated at $75,000. Details of work are as follows:

1. Repairs prior to implementing countermeasures, (including filling missing mortar joints, removing debris from channel bed, filling scour holes and gaps between the bottom of footing and top of soil next to south abutment, with concrete)
2. Constructing concrete aprons (including cofferdams and de-watering)
3. Providing riprap at abutments & wingwalls

For Water St. Bridge underpinning the East abutment footing will be expensive and requires bridge closure. Previous repairs, such as reconstructing the apron footing have not worked due to shallow depth of foundation in the original construction.

Replacement of bridge is likely to take several years and during this period interim countermeasures are required (Ref. 4). Riprap placement requires a 3 feet minimum depth below the riverbed (Fig. 2). Cost of interim countermeasures are estimated at $67,000. Details of work are as follows:

1. Repairs prior to implementing countermeasures, (including removing debris from channel bed, and filling scour holes).
2. Building temporary cofferdam and de-watering, filling gap below the bottom of footing at east abutment with concrete for approximately 20 ft. length.
3. Placing grout bags at east abutment (including textile layer).

GUIDELINES AND CONCLUSIONS

The procedures developed here represent the current state of art in USA, as presented in a flow diagram and serve as practical basis of any similar scour study.

1. **Investigation of factors affecting stream and foundation stability:** It was confirmed that both the bridges are scour critical and the bridge footings have become unstable. Abutments are skewed to the direction of flow, and the existing footing elevation is placed above the computed scour depth. There are no existing river training measures or foundation armoring. Upstream features also affect flood velocities and increased scour.
2. **Organizing data collection:** Due to the variety of in-house and field data required for completing scour analysis, an NJDOT memorandum was adopted. A sample of the format is shown in the Appendix A.

3. **Importance of investigating 'unknown foundation' in scour analysis:** Test boreholes were driven to provide important missing data for footing and rock elevations. This leads to a reliable and economical design of countermeasures.

4. **Streamlining HEC-18 procedures by Flow diagram**: H & H, scour analysis and countermeasures design procedures are summarized in Figure 5, and are recommended for application and reference on similar in-depth studies.

5. **Determining SI &A Coding**: Phase I bridge coding was checked and revised based on extensive Phase II studies. This approach warns of any immediate danger of collapse of footing. Accurate determination of Inventory Codings help in future planning and cost allocations for substructure repairs or for replacement of bridge.

6. **Design of Countermeasures:** For Guinea Hollow Road Bridge, strengthening the footing by apron wall and installation of armoring, such as riprap are recommended. For Water Street Bridge, underpinning the east abutment footing and providing countermeasures for both abutments will approach the cost of a replacement

structure. Hence replacing the 63-year-old bridge appears to be a better choice in economic terms. Interim repairs and replacement of bridge are recommended.

7. **Monitoring:** Continued monitoring of the footings and of the main channel, during routine biennial inspections, will be necessary. Monitoring after floods is also required.

REFERENCES

1. AASHTO Load Resistance Factor Design (LRFD) Bridge Design Specifications, 1998
2. ASCE – Stream Stability and Scour at Highway Bridges, Water Resources Eng., 1999
3. FHWA – Evaluating Scour at Bridges Fourth Edition, HEC No. 18, 2001
4. FHWA – Bridge Scour and Stream Instability Countermeasures, HEC No. 23, 1997
5. FHWA – Federal Coding Guide, 1994.
6. FHWA - Determination of Unknown Subsurface Bridge Foundations, NCHRP Report No. 21-5, Geotechnical Guideline No. 16, 1998
7. Melville B.W. and Coleman S.E. –Bridge Scour, Water Resources Publication, 2000
8. NJDOT Bridge Design Manual 1998

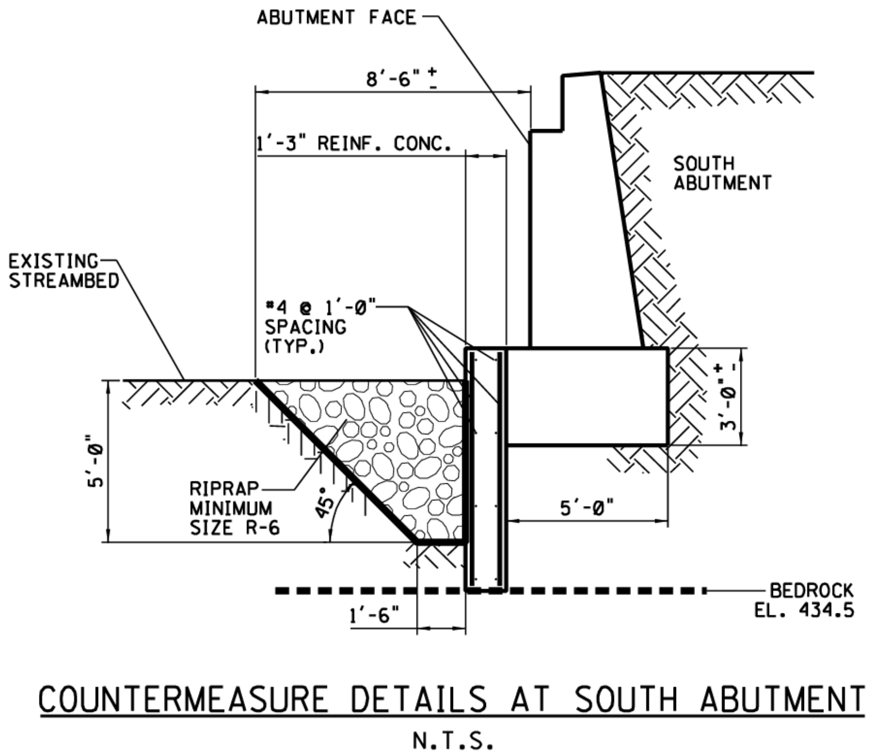


Figure 1. Scour Countermeasures - Structure No. 1000-041
Guinea Hollow Road Over North Branch Rockaway Creek

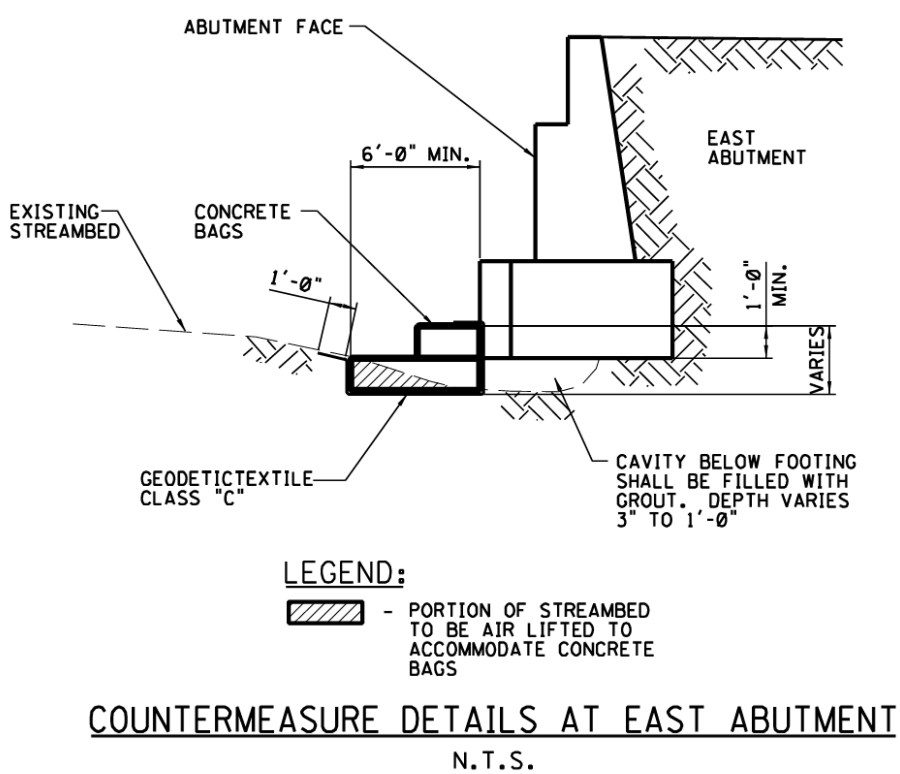


Figure 2. Scour Countermeasures - Structure No. 1000-042
Water Street Over Trib. To North Branch Rockaway Creek

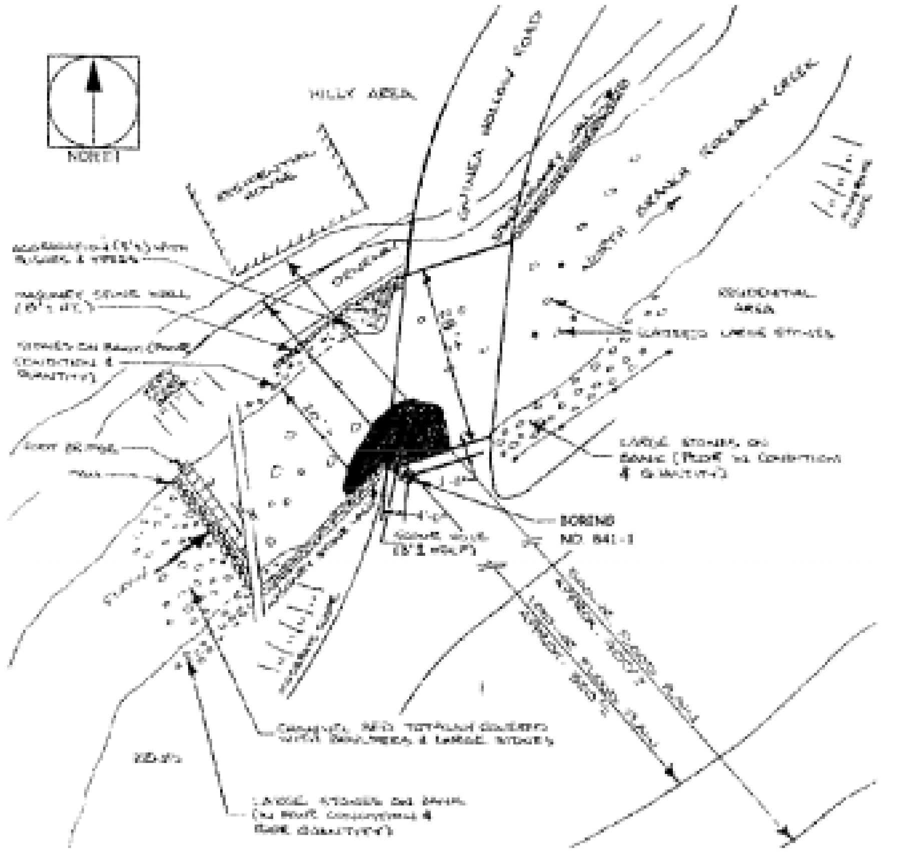


Figure 3. Bridge Plan - Structure No. 1000-041
Guinea Hollow Road Over North Branch Rockaway Creek

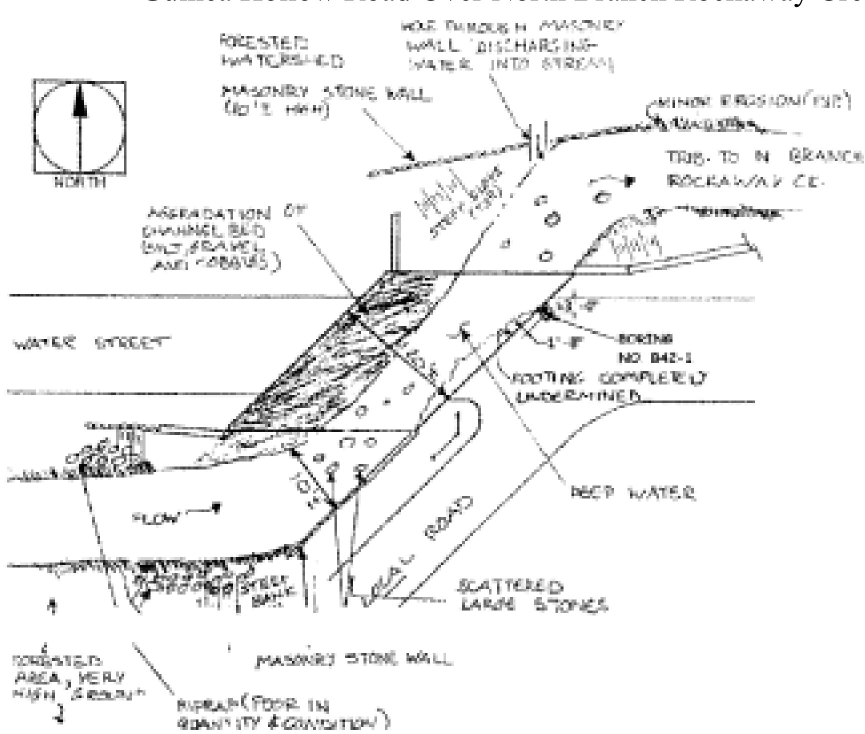
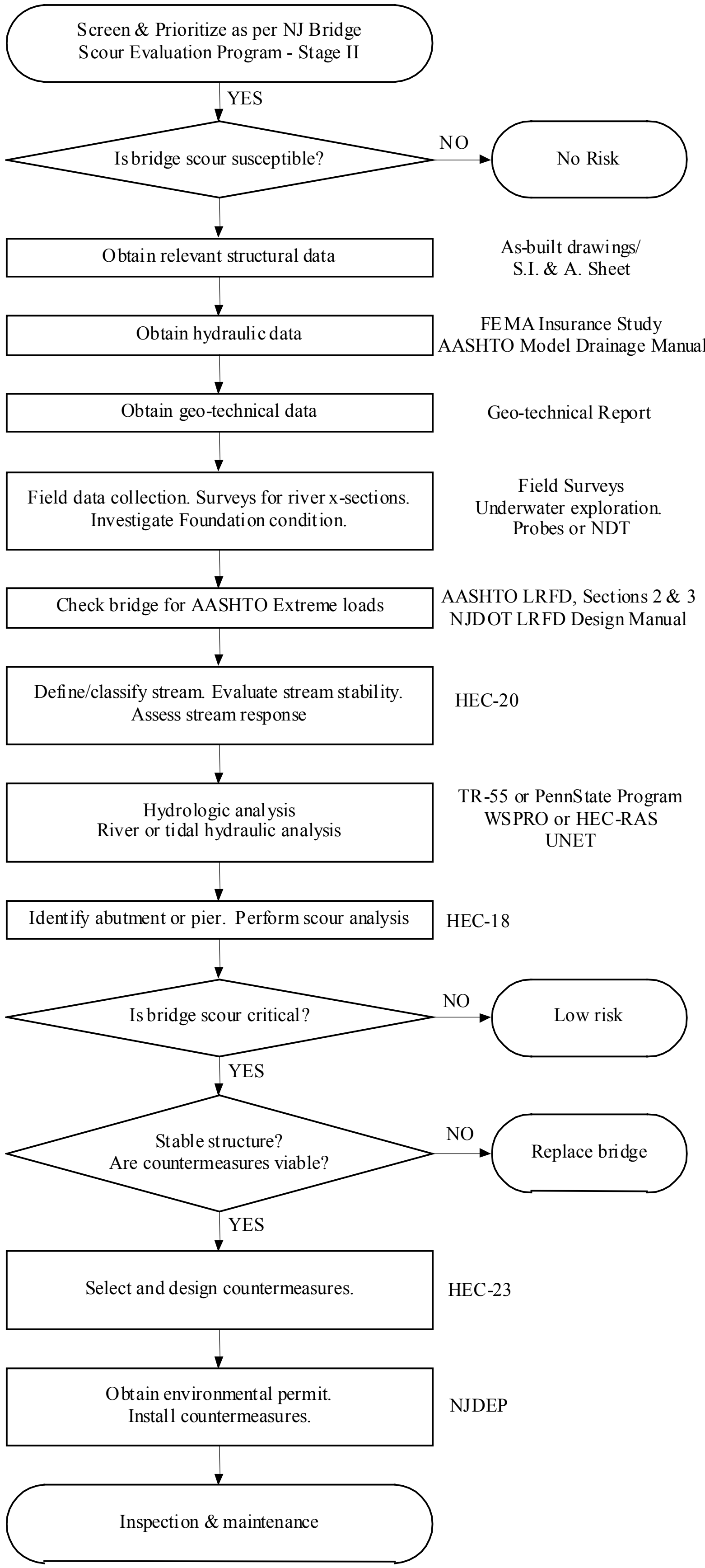


Figure 4. Bridge Plan - Structure No. 1000-042
Water Street Over Trib. To North Branch Rockaway Creek

FIGURE 5 : SCOUR STUDY PROCEDURE FOR EXISTING BRIDGES



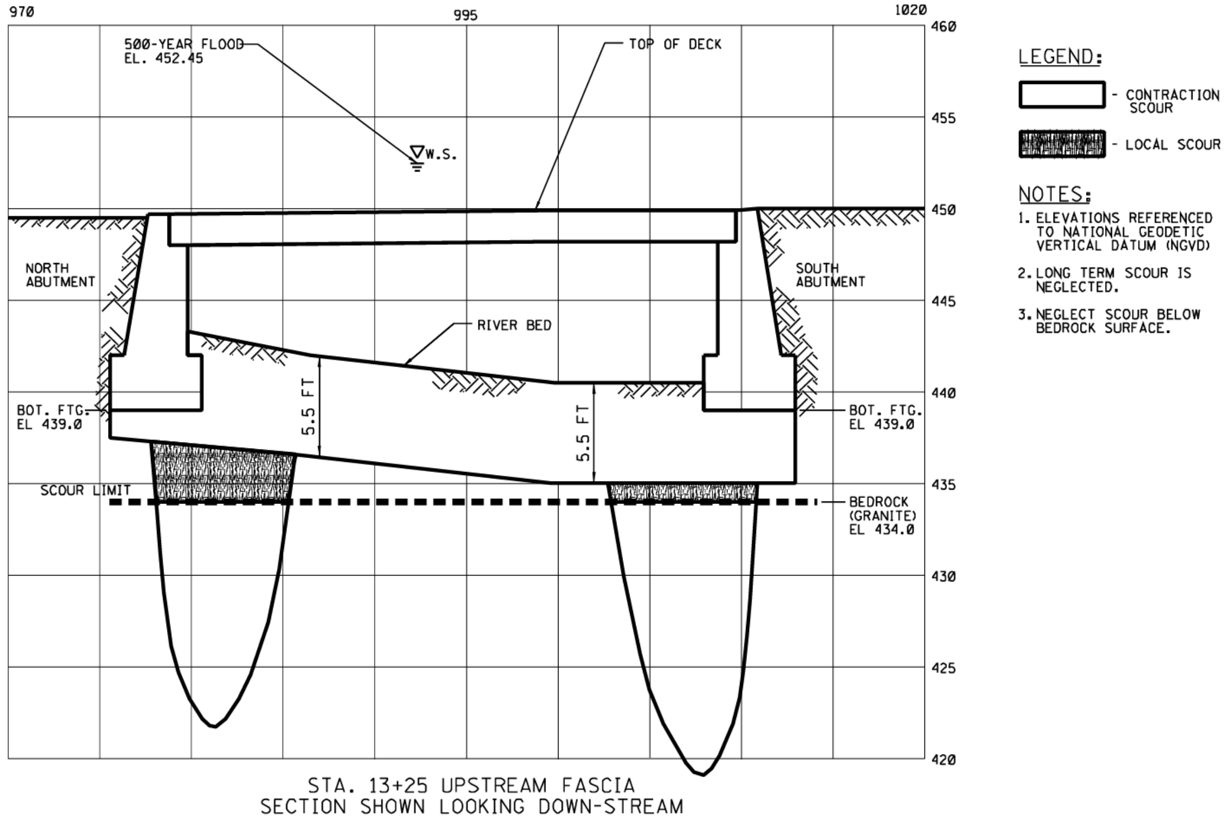


Figure 6. Calculated Scour Depths For 500 Year Flood - Structure No. 1000-041 Guinea Hollow Road Over North Branch Rockaway Creek

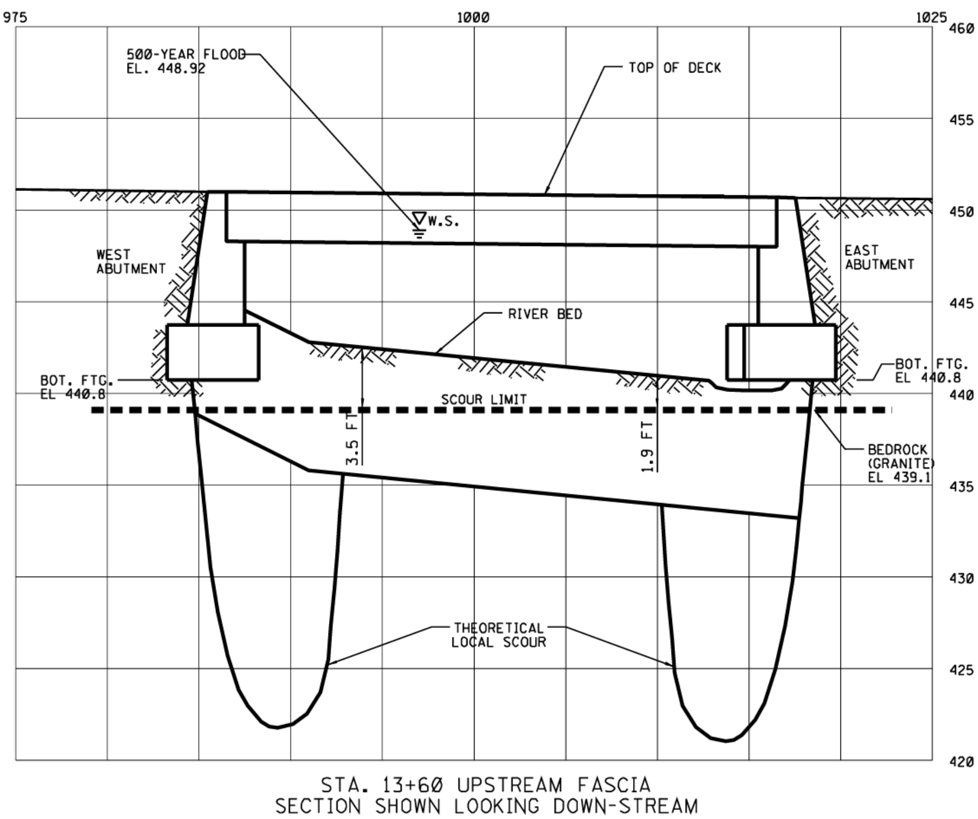


Figure 7. Calculated Scour Depths For 500 Year Flood - Structure No. 1000-042 Water Street Over Trib. To North Branch Rockaway Creek

APPENDIX A - DATA COLLECTION PROCEDURE

- **Design Office Data Survey**

To perform scour analysis, a data collection procedure is required, as follows:

a. Compile an inventory of all reliable field data and data available in the design office.
b. Prepare a list of remaining data, which is necessary to perform scour analysis, and the method, extent and duration of obtaining such data.

- **Field Survey**

Gage Data for peak flood discharges was not available.
A field survey of the two bridges, by a team of licensed structural, hydraulic and geotechnical engineers was carried out during March and April 2001.

The team performed the following tasks:

1. Recorded visual observations for: Scour holes, shift in thalweg of main channel, cracks and open mortar joints in stone masonry abutments, deposit of stones and debris from earlier floods, evidence of river training measures or scour countermeasures in place.
2. Investigated the need to drill test borings to determine depth of rock and the type of bearing material.
3. Prepared photographic documentation
4. Obtained river cross sections.
5. Evaluated stream and waterway characteristics.
6. Evaluated 'n' values (Manning's roughness coefficients).
7. Prepared Data Collection items including purpose and methodology listed below:

Item	Purpose	Data Collection	Methodology for Obtaining data
Field Surveys	Waterway Opening	Yes	Observations and Measurements
Underwater Survey	Scour Holes	Yes	Probing
River Cross-Sections	HEC-RAS Model	Yes	Surveying Instruments
Soil Parameters	Roughness Coefficients/ D50	Inspection & Photos/Grab Samples	Characteristics of banks bed material. Visual & Sieve Analysis
Foundation Details	Size and Scour Damage	Inspection & Photos	Probing and Exposed Footings
Test Boring	Depth of Footing / Rock	Boring Log	Drilling / Coring

APPENDIX B – SCOUR ANALYSIS

Hydrologic & Hydraulic Analyses

Discharges for 50 year, 100 year and 500 year storms were calculated for the watershed based on the Stankowski Regional Equations found in "Magnitude And Frequency of Floods in New Jersey with Effects on Urbanization" (Special Report 38, by Stephen J.

Stankowski, U.S. Geological Survey). This is the preferred method for determining storm flows in New Jersey. The Stankowski Regional Equation is based on a thorough study of relationships between flood data and meteorological characteristics for 103 sites in the state. The parameters for the Stankowski Regional Equation are drainage area, channel slope, surface storage index, and index of manmade impervious cover.

The water surface profile was determined using HEC-RAS version 3.0 software (Ref. 2). FEMA study based on HEC-2 study is available only for Guinea Hollow Road bridges. However, the existing cross sections were determined to be outdated (over 20 years old) and inaccurate as a result of potential sedimentation and erosion over many years. The new input data consisted of eight recently surveyed cross sections, five upstream and three downstream.

SCOUR DEPTHS

Scour analysis was performed in accordance with HEC-18 (Ref. 3) and NJDOT Design Manual, Section 46 (Ref. 8). The intent of HEC-18 is to establish methods for estimating various scour components for use in conjunction with engineering judgement, to evaluate potential depth of total scour. Calculated scour depths are summarized in Tables 1 and 2. Modes of bed transport were Live Bed and Clear Water. Excel Spreadsheets were developed based on applicable methods and formulae (Ref. 3, 7 and 8). Sample results are summarized in Tables 1 and 2 and are plotted in Figures 6 and 7.

- **Long Term Scour**

Field observations and past inspection reports did not reveal evidence of continuing or significant long term aggradation or degradation. Any long term scour was neglected.

- **Contraction Scour**

This occurs mainly from the contraction of flow area, which results in increased velocity and shear stress on channel bed.
The computation of critical velocity was based on Laursen's equation
$\mathbf{V_C = 10.95\ (y_1)^{1/6}\ x\ (D_{50})^{1/3}}$ (Eq. 5.1, Page 5.2).
A comparison was made with the mean velocity value obtained from HEC-RAS analysis. Modified Laursen's eq. for Live Bed mode determined the depth of contraction scour.
Live Bed Contraction Scour $\mathbf{y_2/y_1 = (Q_2/Q_1)^{6/7} x\ (w_1/w_2)^{k1}}$ (Eq. 5.2, Page 5.10)
Another modified Laursen's equation for Clear Water mode was used.
$\mathbf{y_2 = (K_u Q^2/(D_m^{2/3}\ x\ w^2))^{3/7}}$ (Eq. 5.4, Page 5.13)
$\mathbf{y_s = y_2 - y0}$ (Eq. 5.5, PAGE 5.13)

- **Local Scour**

Froehlich's Equation is given by

$\mathbf{y_s = (2.27 \times K_1 \times K_2 (L'/y_a)^{0.43} \times Fr^{0.61} + 1) y_a}$ (Eq. 7.1, Page 7.8)

This occurs from vortices, which are caused by flow obstructions and are cyclic in nature. Based on the ratio of projected abutment length to flow depth (L/y1)< 25, either Froehlich's equation or Hire's equation for live bed scour was used to estimate potential depth of local scour at each abutment. Resulting scour depths estimated by Froehlich's equation seem excessive. However HEC-18 states that the equation be used to aid in the placement of countermeasures. Therefore calculated depths will be treated as an estimate of potential depth of scour.

HIRE's Equation is given by $\mathbf{y_s} = \mathbf{y_1 \times 4 \times Fr^{0.33} \times K_1 K_2 / 0.55}$ (Eq. 7.2, Page 7.9)

Total scour depth = Depths of (Long term scour + Contraction scour + Local scour)