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# Case Study: An Analysis of Pier Scour Using the SRICOS Method

**By Ki Seok Kwak* and Jean Louis Briaud****

## Abstract

In the process of the bridge design, especially the determination of width and length of pier foundations, the scour depth around the bridge could be very important factor for the economic and safe design of the bridge. The Woodrow Wilson bridge across the Potomac River in Washington D.C. is a six lane bridge which is being replaced by a twelve lane bridge due to the rapid growth of traffic. In this study, the scour depths are calculated for the existing bridge by using the SRICOS method, which has been developed to predict the evolution of the local scour depth at a bridge pier founded in soil or soft rock and compared with the measured scour depths. The scour depths of the replacement bridge are also calculated and discussed for the design purposes. The soil samples are taken from the bridge site by using thin wall Shelby tubes and tested in the EFA (Erosion Function Apparatus) to obtain the erosion function. The discharge hydrograph for the entire bridge life is obtained from the USGS website. Using these hydrologic and geotechnical data, the scour analyses were performed for the selected bridge piers. The E-SRICOS method and the S-SRICOS method give reasonable predictions.

*Keywords: erosion, foundation, scour, shear stress, cohesive, clays*

## 1. Introduction

Non-cohesive soils resist erosion only by their buoyant weight and the friction between the particles, on the other hand, the behavior of cohesive soils against erosion is complex and depends on many factors including the electrostatic and Van der Waals forces. Fine-grained soils composed of or containing significant fractions of cohesive materials have greater resistance against scour than coarse-grained soils composed of non-cohesive materials. Therefore, scour in cohesive soils is much slower and more dependent on soil properties than that in non-cohesive soils.

The Woodrow Wilson bridge across the Potomac River in Washington D.C. is a six lane bridge which is being replaced by a twelve lane bridge due to the rapid growth of traffic. The soils below the main channel bed are mostly alluvial deposits, which consist of soft clay, silt and silty sand. In this study, the scour depths are calculated for the Woodrow Wilson bridge by using the SRICOS method, which has been developed to predict the evolution of the local scour depth at a bridge pier founded in cohesive soils or soft rock and compared with the measured scour depths. The results are also compared with the scour depths obtained using HEC-18 (Richardson and Davis, 1995) which was based on experiments conducted in non-cohesive materials for the comparison purpose.

## 2. The Existing Woodrow Wilson Bridge

The existing Woodrow Wilson bridge is located in Prince George County (Maryland), Alexandria (Virginia) and Washington (D.C.) and carries Interstate Routes 95 and 495 over the Potomac River. This bridge is an essential element of the I-495/95 beltway around Washington D.C. Due to the rapid growth of traffic, a replacement bridge is being designed to handle future demand safely and efficiently.

The existing Woodrow Wilson bridge is a draw bridge which has 58 spans and is approximately 1,800 m long. It was opened to traffic in 1961 with a design capacity of 75,000 vehicles per day. The design capacity was reached just 8 years after completion of the bridge (1969). In 1998, approximately 190,000 vehicles were using the bridge everyday. The projected 2020 average daily traffic volume is 300,000 vehicles per day. The main river piers of the existing bridge are massive and embedded in the river bed. The width of the piers which cross over the river channels and the shape of the front of the piers are listed in Table 1.

*Member, Senior Researcher, Civil Engineering Division, Korea Institute of Construction Technology (E-mail: kskwak@kict.re.kr)
**Spencer J. Buchanan Professor, Department of Civil Engineering, Texas A&M University.

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Table 1. Pier Parameters and Measured Scour Depths for the Existing Woodrow Wilson Bridge

| Pier | Shape | Width (m) | Measured Scour Depth (m) | |
|---|---|---|---|---|
| | | | Min. | Max. |
| 3W | Square | 2.51 | 1.31 | 2.72 |
| 2W | Square | 2.51 | 0.97 | 1.46 |
| 1W | Square | 9.75 | 0.92 | 2.14 |
| 1E | Square | 9.75 | 1.22 | 1.79 |
| 2E | Square | 2.51 | 0.76 | 3.13 |
| 3E | Square | 2.51 | 1.53 | 2.80 |
| 4E | Square | 2.51 | 1.98 | 3.28 |
| 5E | Circle | 1.68 | 0.77 | 1.72 |
| 23E | Circle | 1.22 | 0.37 | 0.64 |
| 24E | Circle | 1.22 | 0.37 | 0.60 |
| 25E | Circle | 1.22 | 1.01 | 1.50 |
| 26E | Circle | 1.22 | 0.76 | 0.88 |
| 27E | Circle | 1.22 | 0.73 | 1.15 |
| 28E | Circle | 1.22 | 0.61 | 0.73 |
| 29E | Circle | 1.22 | 0.31 | 0.52 |

The location of the piers can be found in Fig. 1. All piers are founded on piles.

At the bridge site, the Potomac River can be divided in three areas: the main channel, the secondary channel and the median area between the two channels. The main channel is near the west shore and is approximately 305 m wide; the secondary channel is along the east shore and is approximately 275 m wide. Fig. 1 shows a best estimate of the soil profile along the existing Woodrow Wilson bridge and the replacement Woodrow Wilson bridge. Some soil properties are listed in Table 2.

## 3. The Replacement Woodrow Wilson Bridge

The replacement bridge will be built immediately south of the existing Woodrow Wilson bridge. The proposed design has two parallel six-lane bridges to replace the existing single six-lane bridge and incorporates a drawbridge for ship traffic. The overall cost of the project including the approach embankments and associated interchanges is estimated at 2.2 billion dollars. The new bridge will have fewer but wider piers than the existing bridge. The piers are designed to have exposed pile foundations to be capped near the water surface. The two bascule piers that support the drawbridges will be protected from vessel impact by a fender system (Jones, 2000). Large dolphins were considered at one point.

The foundation of pier M1 which is one of the bascule piers is shown in Fig. 2. The dimensions of all the piers are shown with the scour result in Table 6. The foundation system for the replacement Woodrow Wilson bridge evolved continuously as design proceeded. The pier sizes, the dolphin diameter and the deep foundation dimensions mentioned are the ones considered during this study but not necessarily those that will be finally retained.

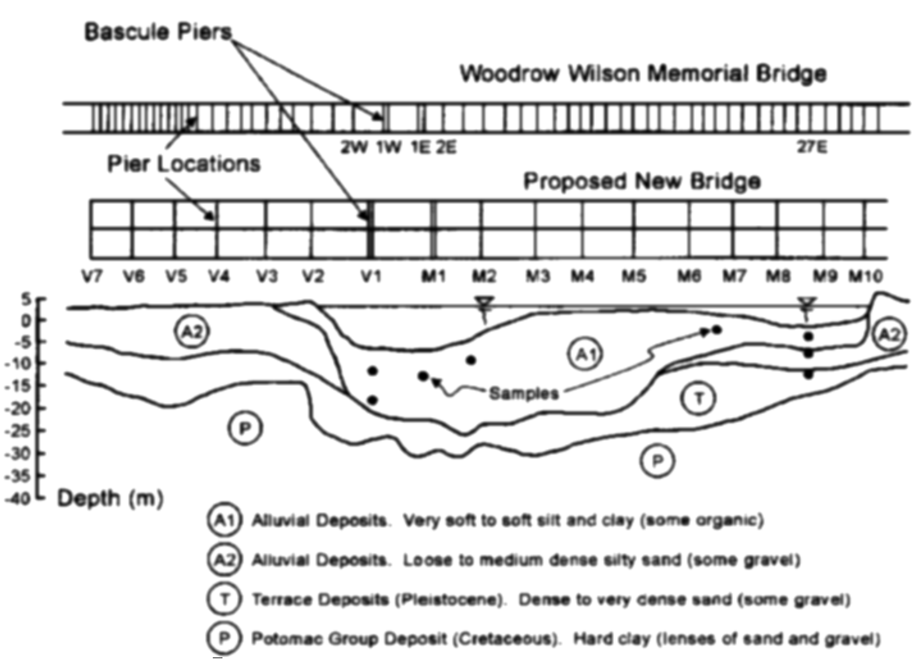

Fig. 1. Estimated Soil Stratigraphy at the Woodrow Wilson Bridge Location

Table 2. Soil Properties of the Soil Samples from the Woodrow Wilson Bridge Site

| Sample Location | Depth (m) | Soil Type | Undrained Shear Strength (kPa) | Bulk Density (kN/m$^3$) | % Passing #200 | Liquid Limit (%) | Plastic Limit (%) | Water Content (%) | Critical Shear Stress (N/m$^2$) | Initial Erodibility |
|---|---|---|---|---|---|---|---|---|---|---|
| Pier 1W | 4.0-4.6 | Clay | 11.5 | 18.1 | 57 | 53 | 12 | 56 | 3.90 | 4.0 |
| Pier 1W | 10.1-10.6 | Clay | 19.0 | 15.6 | 71 | 51 | 18 | 35 | 10.20 | 1.9 |
| Pier 2E | 5.5-6.1 | Clay | 14.0 | 18.5 | 48 | 47 | 14 | 29 | 1.30 | 182.9 |
| Pier 4E | 5.5-6.1 | Sandy Clay | 14.1 | 16.3 | 64 | 37 | 14 | 35 | 0.43 | 9.0 |
| Pier 21E | 2.1-2.7 | Clay | 6.1 | 15.4 | 86 | 68 | 13 | 47 | 1.92 | 2.7 |
| Pier 27E | 2.6-3.2 | Organic | 22.0 | 15.2 | 40 | – | – | 82 | 5.09 | 11.2 |
| Pier 27E | 5.2-5.6 | Silt | – | 15.2 | 73 | 43 | 39 | 66 | 3.80 | 91.0 |
| Pier 27E | 11.2-11.7 | Clay | 130.0 | 21.3 | 78 | 86 | 14 | 24 | 0.16 | 3.2 |
| Pier 27E | 11.9-12.5 | Sand | 12.0 | 17.1 | 9 | – | – | 59 | 0.025 | 1665.2 |

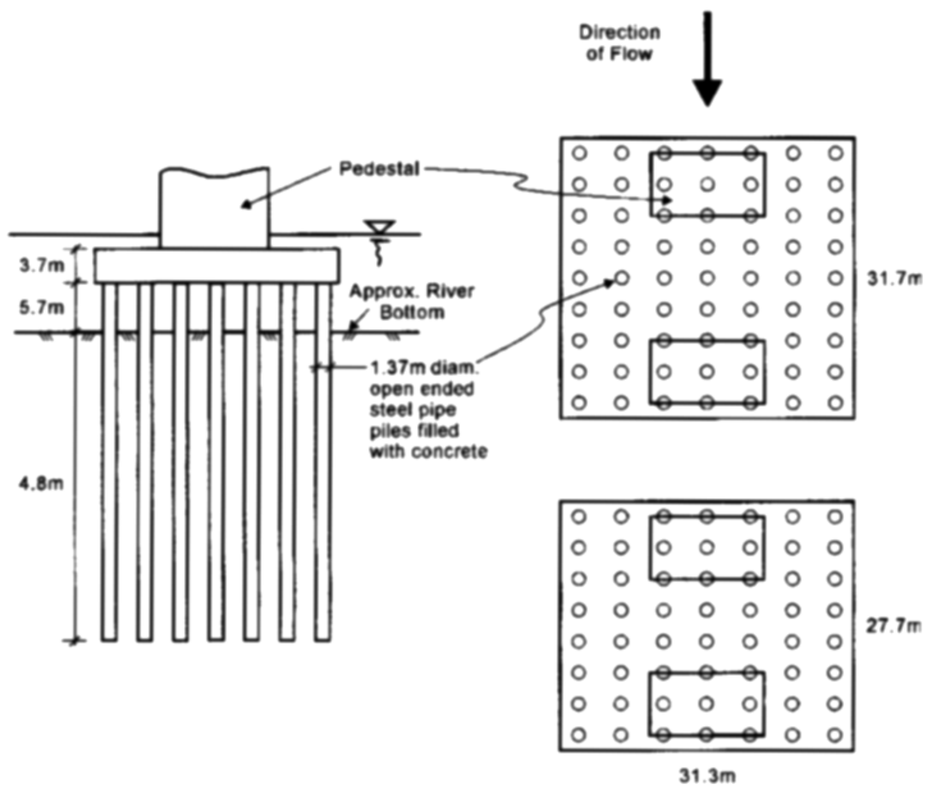


Fig. 2. Foundation of Pier M1 of the Replacement Woodrow Wilson Bridge Considered for Scour Calculations

## 4. The SRICOS Method

The development of the scour depth in fine-grained soils is generally much slower than in coarse-grained soils. Applying the equations for coarse-grained soils to fine-grained soils regardless of time appears to be overly conservative. Therefore, a scour analysis method for fine-grained soils needs to consider the time effect as well as soil properties, hydraulic parameters and pier size.

Because the soil at the site of the Woodrow Wilson bridge is fine-grained (cohesive), the SRICOS method (Briaud *et al.*, 1999 a and b ; Kwak, 2000 ; Briaud *et al.*, 2001a and b) was used. A brief summary of this method is described as a necessary background. The SRICOS method was developed to predict the scour depth $z$ versus time $t$ curve around a cylindrical bridge pier. This method has already been described in details in the references cited. The SRICOS method recognizes that the scour process is highly dependent on the shear stress $\tau$ imposed by the flowing water at the soil-water interface. Through tests performed on soil samples from the bridge site using the EFA (Erosion Function Apparatus), the scour rate $\dot{z}$ versus the shear stress $\tau$ is obtained; this $\dot{z}$ vs. $\tau$ curve is the erosion function. Using this relationship and the maximum scour depth equation, a hyperbolic function describing the scour depth $z$ versus time $t$ curve can be developed. The SRICOS method was extended to include a random velocity-time history and a multilayer soil stratigraphy; it is called the E-SRICOS method (Kwak *et al.*, 2001). The E-SRICOS method requires the use of a simple computer program and gives the scour depth versus time curve for a given hydrograph. The S-SRICOS which is a simplified version of the E-SRICOS method only requires simple hand calculations and gives the final scour depth at the end of the bridge life. The S-SRICOS method is based on the assumption that the actual velocity hydrograph at a bridge site can be transformed into constant velocity flow lasting an equivalent time $t_e$. By definition, the equivalent time $t_e$ is the time required for the maximum velocity in the hydrograph to create the same scour depth as the one created by the complete hydrograph.

## 5. Hydrologic Data

The drainage basin at the Woodrow Wilson (WW) Bridge on the Potomac River has an area of 30,742 square kilometers. It is comprised of portions of Pennsylvania, West Virginia, Virginia, Maryland and Washington, D.C. The nearest gaging station (Gage Station 01646500) was found at the USGS web site. This gaging station is located on the Potomac River approximately 13 km upstream of the Woodrow Wilson Bridge near the Little Falls pump station and has a drainage area of 29,965 km$^2$. The discharge hydrograph was downloaded from the web site, multiplied by the drainage area ratio (30742/29965) and prepared as an input to the SRICOS program. The discharge hydrograph at the bridge site, calculated in such a way, is shown in Fig. 3. The maximum discharge occurred in 1972 and was 9850 m$^3$/s.

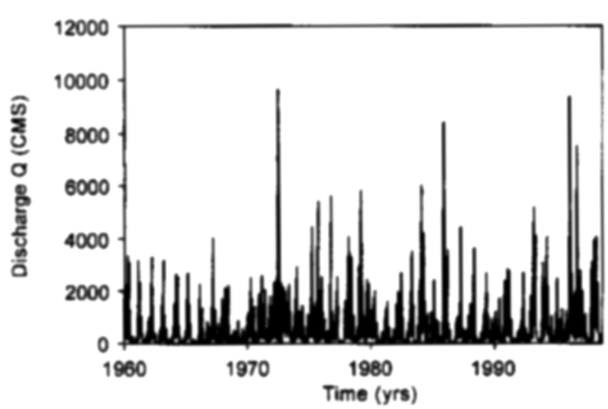


Fig. 3. Discharge Hydrograph at Woodrow Wilson Bridge (01/01/1960-09/31/1998)

In this study, the computer program entitled Hydrologic Engineering Centers River Analysis System (HEC-RAS, 1997) developed by the United States Army Corps of Engineers was used for flood analysis. The input to this program is the average slope of the channel bed, the river bed cross-section profile, Mannings roughness coefficient and many selected discharges varying from 0 to the maximum discharge. The output of this program is the velocities and the water depths at the bridge pier location had the bridge not been there; the velocities and water depths correspond to the input discharges. The relationship between velocity and discharge and between water depth and discharge can then be obtained by regression. Using these relationships, the discharge hydrograph, which is the flow discharge versus time curve, is transformed into the water depth hydrograph and more importantly into the velocity hydrograph or velocity versus time curve used in the SRICOS program. The relationship between velocity and discharge for pier 1E and 27E of the existing Woodrow Wilson Bridge are shown in Fig. 4 and 5. Pier 1E is in the main channel and pier 27E

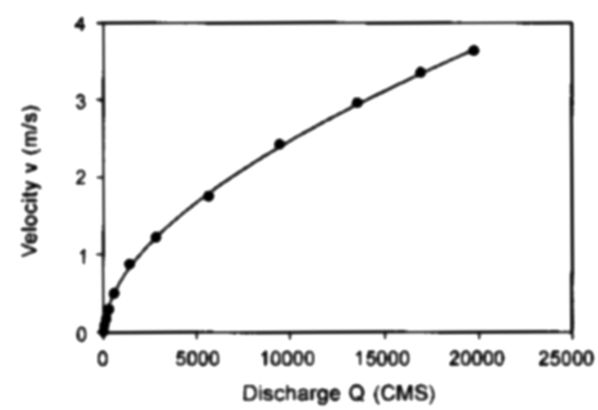


Fig 4. Relationship between Velocity and Discharge (Pier 1E at the Existing Woodrow Wilson Bridge

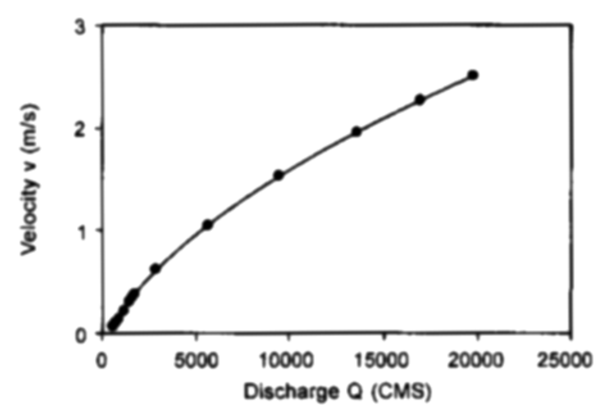


Fig 5. Relationship Between Velocity and Discharge (Pier 27E at the Existing Woodrow Wilson Bridge

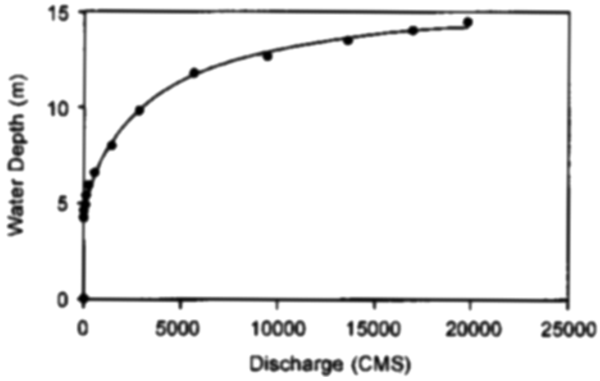


Fig 6. Relationship between Water Depth and Discharge (Pier 1E at the Existing Woodrow Wilson Bridge, Main Channel Pier)

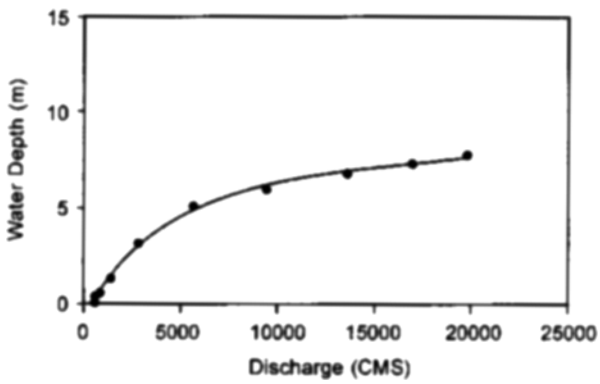


Fig. 7. Relationship between Water Depth and Discharge (Pier 27E at the Existing Woodrow WilsonBridge, Secondary Channel Pier)

in the secondary channel. In order to obtain the water depth history which is needed for considering the water depth effect or wide pier effect, the relationship between water depth and discharge was also prepared for the two selected piers (Figs. 6 and 7). The water depth hydrographs are shown in Fig. 8 over the length of the existing bridge from 1960 to 1999.

## 6. Geotechnical Data

The Woodrow Wilson Bridge over the Potomac River in Washington D.C. is located within the Atlantic Coastal Plain Province which consists of a broad belt of flat-lying sediments over deep bedrock. Throughout the area, the ground surface has been altered in historic times by man-made fills especially in low lying areas and along rivers and streams. The soils below the main channel bed are mostly alluvial deposits, which consist of soft clay, silt and silty sand, extending down to approximately 25 m over the layer of Pleistocene deposits which consist of dense sand, silt and gravel.

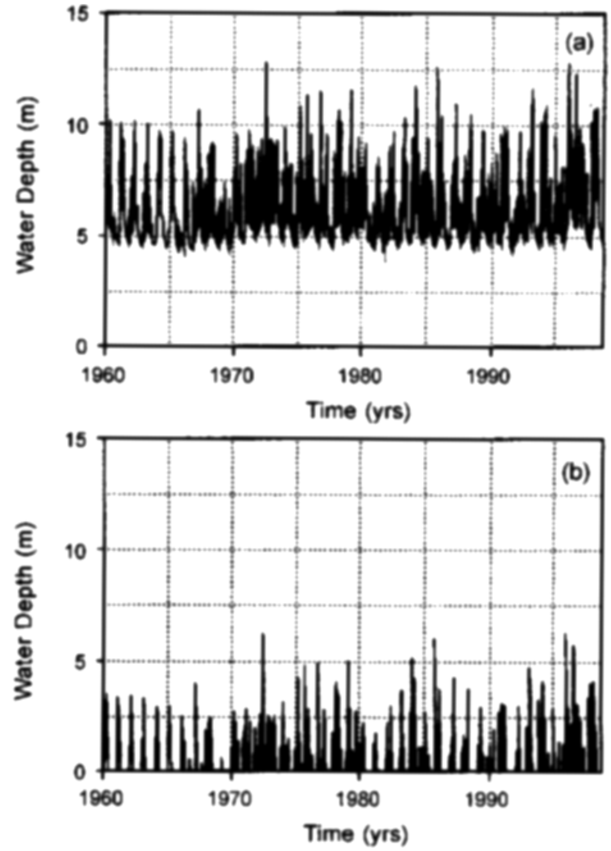


Fig. 8. Water Depth Hydrograph for the Existing Woodrow Wilson Bridge: (a) Pier 1E, (b) Pier 27E

For this study, soil samples were taken near the location of piers 1W, 2E and 4E in the main channel and piers 21E and 27E in the secondary channel by using thin-wall shelby tubes with 76.2 mm outside diameter. The drilling locations are shown in Fig. 1 with the stratigraphy. The soil samples were tested using the EFA. Before performing the EFA tests, basic soil properties were obtained by performing laboratory tests. All the soil property tests were conducted according to American Society for Testing and Materials (ASTM) standards. The undrained shear strength of the soil was measured at least twice using the vane test. The results of the soil property tests are shown in Table 2.

The purpose of the EFA test is to obtain the curve that relates the scour rate $\dot{z}$ to the shear stress $\tau$ induced by the flowing water. The water flows over the sample at a chosen velocity and the sample is advanced 1 mm as soon as it is eroded. These experiments are performed repeatedly for six or seven different velocities varying between 0.1 m/s and 5 m/s on each Shelby tube sample. The flowing water generates an average bed shear stress over the soil sample in the test section. The range of $\tau$ values imposed is approximately 0.1 N/m$^2$ to 100 N/m$^2$. The hydraulic shear stress imposed by the water on the soil is calculated by using

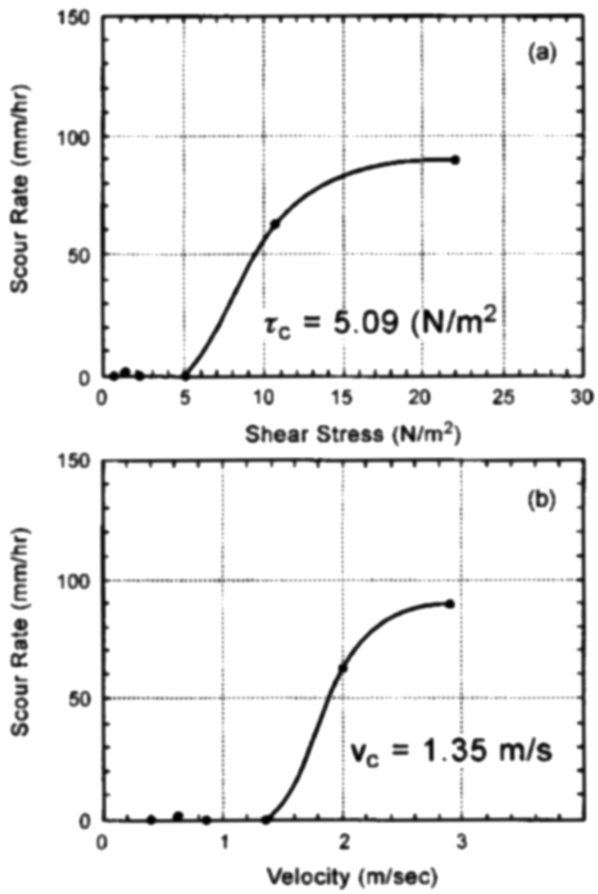


Fig. 9. Erosion Function for a Soil Sample Taken Near Pier 27E of the Existing Woodrow Wilson Bridge (2.6 3.2 meters depth): (a) Scour Rate vs. Shear Stress, (b) Scour Rate vs. Velocity

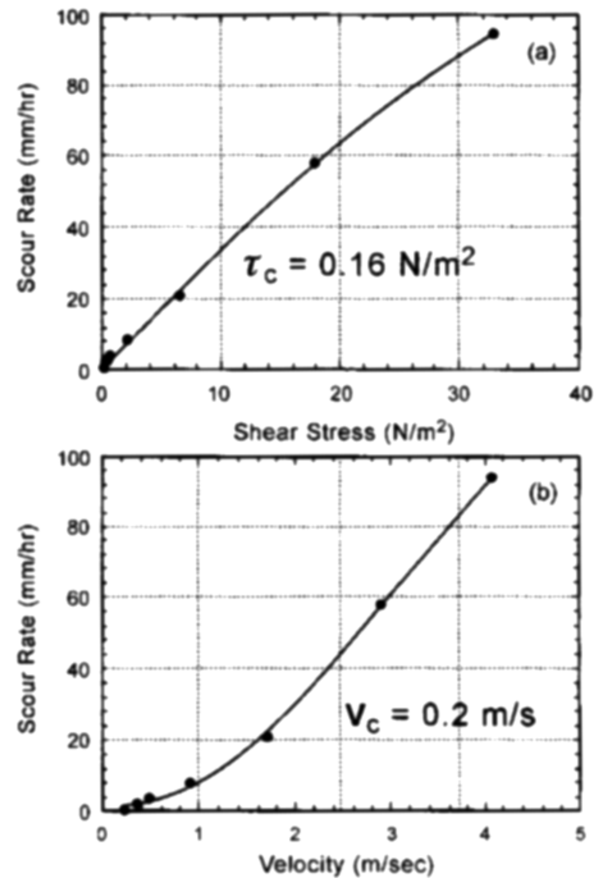


Fig. 10. Erosion Function for a Soil Sample Taken Near Pier 27E of the Existing Woodrow Wilson Bridge (11.2 11.7 meters depth): a) Scour Rate vs. Shear Stress, b) Scour Rate vs. Velocity

Moody Chart (Moody, 1944). The critical shear stress is considered to be the shear stress when the scour rate is equal to 1 mm/hr. This number is used as a practical definition of the critical shear stress.

The erosion functions, scour rate $\dot{z}$ versus shear stress $\tau$, were obtained for all the samples. Two examples are shown in Figs. 9 and 10. The soil at pier 27E (2.6-3.2 m depth) is a soft organic clay and the undrained shear strength is relatively low (22.0 kPa), however, the critical shear stress $\tau$ is relatively high (5.09 N/m$^2$, Fig. 9). The soil at pier 27E (11.2-11.7 m depth) is a hard mineral clay and the undrained shear strength is relatively high (130.0 kPa) however, the critical shear stress is relatively low (0.16 N/m$^2$ Fig. 10). In order to investigate the influence of cohesive soil properties on the erosion function, two erodibility parameters were defined: the critical shear stress $\tau_c$ and the initial erodibility $S_i$ which is the initial slope of the erosion function. The two erodibility parameters $\tau_c$ and $S_i$ were plotted against soil properties such as plasticity index, undrained shear strength and percent passing sieve #200. All correlations were poor. In Fig. 11, the correlations between critical shear stress, initial erodibility and undrained shear strength are shown with the data from a previous study (Briaud *et al.*, 2001a). The poor correlations lead to think that obtaining these parameters by direct measurement in the EFA is more reliable than using correlations.

## 7. Measured Scour Depth

The existing Woodrow Wilson Bridge is approximately 1,800 m long and has 58 spans (57 piers). The piers are numbered beginning at the center of the bascule section in the main channel and increase as they approach each shore. Piers 1W through 26W are on the west side and piers 1E through 31E are on the east side. All the piers and abutments are made of reinforced concrete and are founded on piles. The junction between the pier and the piles is well below the current scour depth. In other words, the width to be considered for scour analysis is the pier width not the piles width.

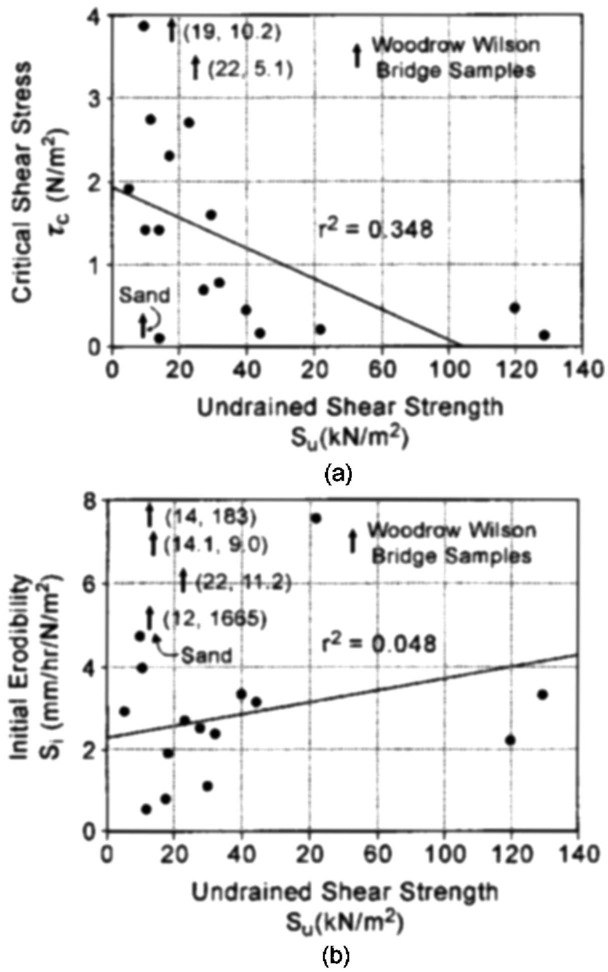


Fig. 11. Lack of Correlation Between Critical Shear Stress, Initial Erodibility and Undrained Shear Stress (after Briaud *et al.*, 1999 (b))

Some piers on the west side (4W to 26W) and some piers in the median area (6E to 22E) are not considered in the scour analysis because these piers are not over water. The parameters for the piers in water are shown in Table 2. The attack angle of the flow is 0° for all the piers.

The channel bed was monitored in 1998. The scour measurement results for each pier are shown in Table 1. The depth of local scour is defined here as the difference between the bed level at the pier and the bed level away from the pier. The bed level away from the pier is typically taken as the average of several points measured in the unscoured region around the obstruction. In this study, there was some ambiguity on the measured local scour depth because several interpretations of the scoured bed profile were possible. An example is shown in Fig. 12 for pier 5E. It was decided to use a range of possible values in all cases; Fig. 12 shows an example of minimum and maximum values. All values are listed in Table 1.

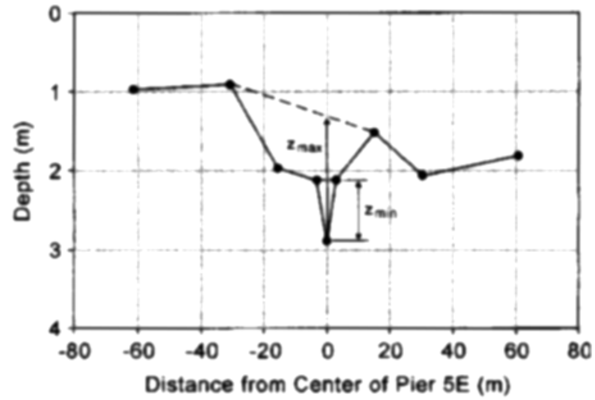


Fig. 12. Potomac River Bottom Profile Around Pier 5E of the Existing Woodrow Wilson Bridge

## 8. Results of Analyses

The scour depth $z$ versus time $t$ curves were calculated for each pier of the existing bridge over the time period from 1960 to 1999. This period spans from the date the bridge was built to the date this study was performed. When soil samples were not taken from the exact pier location, the

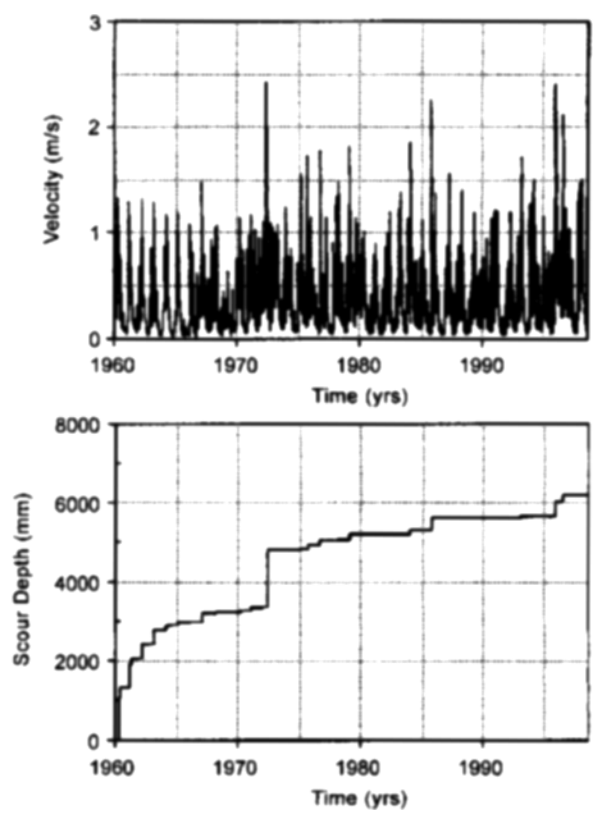


Fig. 13. Velocity Hydrograph and Predicted Scour Depth vs. Time Curve for Pier 1E of the Existing Woodrow Wilson Bridge

erosion function of the nearest soil samples was used as input to the SRICOS program. Examples for two representative piers of the existing bridge in the main and secondary channels (Pier 1E and 27E) are shown with the respective velocity hydrographs in Figs. 13 and 14.

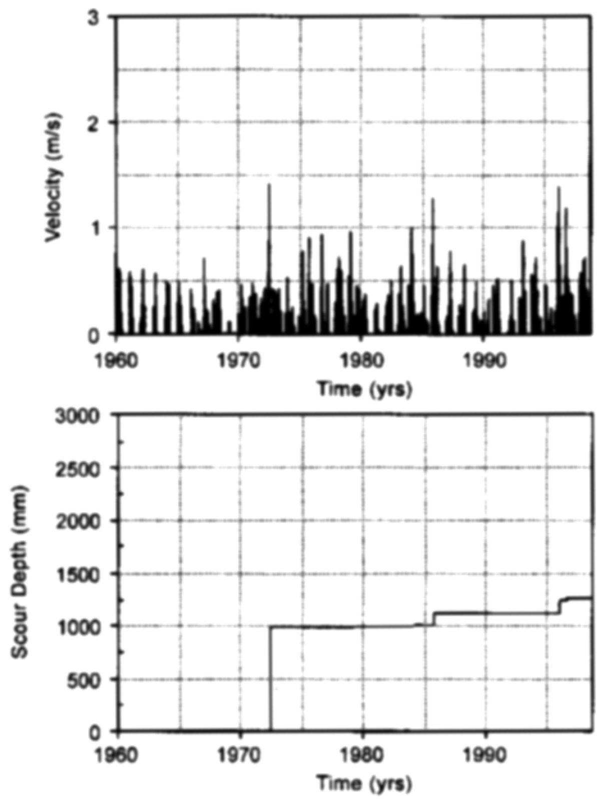


Fig. 14. Velocity Hydrograph and Predicted Scour Depth vs. Curve for Pier 27E of the Existing Woodrow Wilson Bridge

In every case, the predicted final scour depth $z$ does not reach the predicted maximum scour depth $z_{max}$ even though the life of the existing bridge is about 39 years. The values of $z$ and $z_{max}$ are compared in Table 3. The ratio of

Table 3. Predicted Scour Depths at the Existing Woodrow Wilson Bridge Using E-SRICOS Method

| Pier | Final Scour Depth $z$ (m) | Max. Scour Depth $z_{max}$ (m) | $\frac{z}{z_{max}}$ (%) |
|---|---|---|---|
| 3W | 1.64 | 2.85 | 57.5 |
| 2W | 2.92 | 3.66 | 79.8 |
| 1W | 5.72 | 9.21 | 62.1 |
| 1E | 6.14 | 9.51 | 64.6 |
| 2E | 3.69 | 3.97 | 92.9 |
| 3E | 3.34 | 3.57 | 93.6 |
| 4E | 2.61 | 3.28 | 79.6 |
| 5E | 1.07 | 1.89 | 56.6 |
| 23E | 0.47 | 1.22 | 38.5 |
| 24E | 0.52 | 1.25 | 41.6 |
| 25E | 0.17 | 1.29 | 13.2 |
| 26E | 1.07 | 1.54 | 69.5 |
| 27E | 1.41 | 1.74 | 81.0 |
| 28E | 1.40 | 1.74 | 80.5 |
| 29E | 1.36 | 1.71 | 79.5 |

Table 4. Predicted Scour Depths at the Existing Woodrow Wilson Bridge Using S-SRICOS Method

| Pier No. | Length of Hydrograph $t_{hydro}$ (yrs) | Max. Discharge $Q_{max}$ (CMS) | Max. Velocity $v_{max}$ (m/s) | Pier Width $B$ (m) | Max. Scour Depth $z_{max}$ (mm) | Shear Stress $\tau_{max}$ (N/m$^2$) | Initial Scour Rate $\dot{z}_i$ (mm/hr) | Equivalent Time $t_e$ (hrs) | Final Scour Depth $z$ (m) |
|---|---|---|---|---|---|---|---|---|---|
| Pier 3W | 39 | 9850.5 | 1.41 | 2.51 | 2852.4 | 9.85 | 25.77 | 108.6 | 1.48 |
| Pier 2W | 39 | 9850.5 | 2.09 | 2.51 | 3662.2 | 20.04 | 115.73 | 157.4 | 3.10 |
| Pier 1W | 39 | 9850.5 | 2.30 | 9.75 | 9212.6 | 17.92 | 90.88 | 194.5 | 6.25 |
| Pier 1E | 39 | 9850.5 | 2.42 | 9.75 | 9514.9 | 19.62 | 110.47 | 204.0 | 6.88 |
| Pier 2E | 39 | 9850.5 | 2.37 | 2.51 | 3966.6 | 25.14 | 696.67 | 136.2 | 3.82 |
| Pier 3E | 39 | 9850.5 | 2.01 | 2.51 | 3572.6 | 18.68 | 696.67 | 102.8 | 3.42 |
| Pier 4E | 39 | 9850.5 | 1.76 | 2.51 | 3283.6 | 14.70 | 163.50 | 109.6 | 2.81 |
| Pier 5E | 39 | 9850.5 | 1.28 | 1.68 | 1889.8 | 8.92 | 15.03 | 102.6 | 0.85 |
| Pier 23E | 39 | 9850.5 | 0.88 | 1.22 | 1215.8 | 4.79 | 5.88 | 65.3 | 0.29 |
| Pier 24E | 39 | 9850.5 | 0.92 | 1.22 | 1250.6 | 5.19 | 5.88 | 70.4 | 0.31 |
| Pier 25E | 39 | 9850.5 | 0.97 | 1.22 | 1293.3 | 5.72 | 5.88 | 77.1 | 0.34 |
| Pier 26E | 39 | 9850.5 | 1.28 | 1.22 | 1542.4 | 9.47 | 50.59 | 80.5 | 1.12 |
| Pier 27E | 39 | 9850.5 | 1.55 | 1.22 | 1741.7 | 13.40 | 79.16 | 102.0 | 1.43 |
| Pier 28E | 39 | 9850.5 | 1.55 | 1.22 | 1741.7 | 13.40 | 79.16 | 102.0 | 1.43 |
| Pier 29E | 39 | 9850.5 | 1.50 | 1.22 | 1705.8 | 12.62 | 75.78 | 97.3 | 1.39 |

piers averages 66%.

The shape of the scour depth $z$ versus time $t$ curve depends on the scour rate of the soil as well as the shape and intensity of the hydrograph (Kwak, 2000). The scour depth at pier 1E increased gradually and the maximum velocity which occurred in 1972 did not greatly contribute to the scour depth because a certain amount of the scour had already developed when it occurred (Fig. 13). In the case of pier 27E, the maximum velocity in 1972 had a sudden influence on the scour depth because the low velocities prior to 1972 generated shear stresses below the critical shear stress of the soil and no scour developed before 1972 (Fig. 14).

The scour depth for each pier of the existing bridge is also calculated by using the S-SRICOS method. The length of the hydrograph $t_{hydro}$, the maximum velocity $v_{max}$ and the initial scour rate $\dot{z}_i$ of the soil are used to calculate the equivalent time $t_e$. The parameters and the results are shown in Table 4.

Scour analyses for the 100-year and the 500-year floods were also performed for the replacement bridge by using the S-SRICOS method because the S-SRICOS only requires the peak velocity. The peak discharges for the recurrence intervals (100 and 500 years) were obtained from the Maryland State Highway Administration and are shown in Table 5. They were transformed into peak velocity by using HEC-RAS as was done for the existing bridge (Figs. 4 and 5). The equivalent pier width was taken as the sum of the projected widths of the piles obstructing the flow. It was used for these calculations because the piers of the replacement bridge are designed to have exposed pile foundations with the pile cap near the water surface. The SRICOS predictions are shown together with the HEC-18 results in Tables 6 and 7. It is clear that the HEC-18 predicted scour depths are much higher than the SRICOS predicted scour depths.

Table 5. Peak Discharges for the Potomac River at the Woodrow Wilson Bridge

| Recurrence Interval (years) | Peak Discharge (CMS) |
|---|---|
| 100 | 13592 |
| 500 | 19822 |

The predicted scour depths using the E-SRICOS and the S-SRICOS method are compared with the measured scour depths for the existing bridge in Figs. 15 and 16. The piers in the main channel (Pier 2W to Pier 3E) are excluded from the comparison because riprap was placed in the main channel in 1980 to prevent further scour.

As shown in Figs. 15 and 16, the E-SRICOS and S-SRICOS methods give reasonable predictions. The scatter in the predictions may be due to the fact that the erosion function for the soil was not always from samples taken at the scour location. Indeed the samples were taken near piers 4E and 27E. For those piers the coefficient of determination

Table 6. Predicted Scour Depths at Replacement Woodrow Wilson Bridge Using S-SRICOS Method and HEC-18 (100 Year Flood)

| Pier No. | | M10 | M9 | M8 | M7 | M6 | M5 | M4 | M3 | M2 | M1 | Dolphin | V1 | V2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equivalent Pier Width (m) | | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.9 | 6.9 | 9.6 | 13.7 | 9.6 | 6.9 |
| Velocity (m/s) | | 1.80 | 1.80 | 1.80 | 1.80 | 1.16 | 1.16 | 1.16 | 2.80 | 2.80 | 2.80 | 2.80 | 2.80 | 2.80 |
| Water Depth (m) | | 6.86 | 6.86 | 6.86 | 6.86 | 3.60 | 3.60 | 3.60 | 13.62 | 13.62 | 13.62 | 13.62 | 13.62 | 13.62 |
| Scour Depth (m) | S-SRICOS | 3.18 | 3.18 | 3.18 | 1.09 | 0.37 | 0.25 | 0.25 | 7.47 | 7.47 | 7.83 | 7.50 | 7.83 | 6.73 |
| | HEC-18 | 17.07 | 17.07 | 17.07 | 17.07 | 17.07 | 12.31 | 12.31 | 26.64 | 26.64 | 33.10 | 17.68 | 33.10 | 26.64 |

Table 7. Predicted Scour Depths at Replacement Woodrow Wilson Bridge Using S-SRICOS Method and HEC-18 (500 Year Flood)

| Pier No. | | M10 | M9 | M8 | M7 | M6 | M5 | M4 | M3 | M2 | M1 | Dolphin | V1 | V2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equivalent Pier Width (m) | | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.9 | 6.9 | 9.6 | 13.7 | 9.6 | 6.9 |
| Velocity (m/s) | | 2.38 | 2.38 | 2.38 | 2.38 | 1.65 | 1.65 | 1.65 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 |
| Water Depth (m) | | 7.62 | 7.62 | 7.62 | 7.62 | 4.36 | 4.36 | 4.36 | 14.42 | 14.42 | 14.42 | 14.42 | 14.42 | 14.42 |
| Scour Depth (m) | S-SRICOS | 4.90 | 4.90 | 4.90 | 4.73 | 2.37 | 1.99 | 1.99 | 8.86 | 8.86 | 10.36 | 10.66 | 10.36 | 8.55 |
| | HEC-18 | 19.29 | 19.29 | 19.29 | 19.29 | 19.29 | 14.51 | 14.51 | 29.50 | 29.50 | 36.67 | 19.57 | 36.67 | 29.50 |

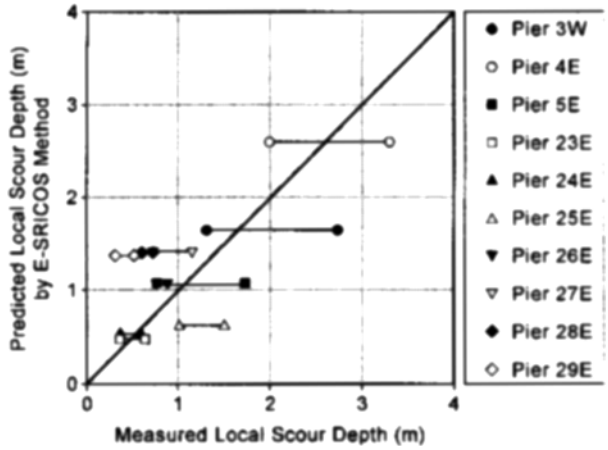

Fig. 15. Comparison of Measured and Predicted Scout Depth (E-SRICOS Method)

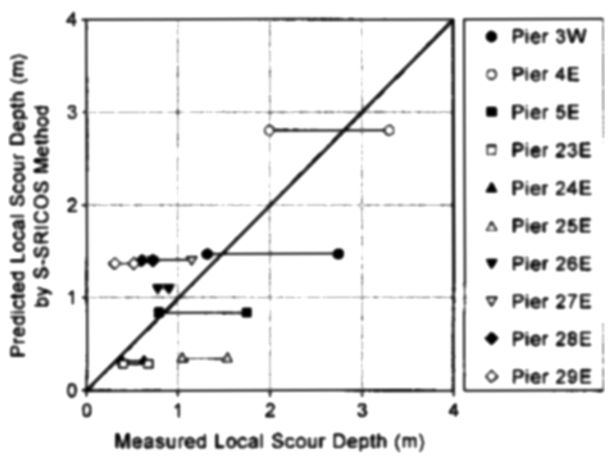

Fig. 16. Comparison of Measured and Predicted Scour Depths (S-SRICOS Method)

($R^2$) is 0.79. For other piers the coefficient of determination ($R^2$) is 0.41. The scatter on Figs. 15 and 16 gives an idea of the factor of safety necessary to minimize the number of cases where the measured scour depth is much larger than the predicted scour depth. It is also very important to note that the larger the scour depth is, the more precise the prediction is.

## 9. Conclusion

The Woodrow Wilson Bridge across the Potomac River in Washington D.C. is being replaced due to the rapid growth of traffic. The scour depths were calculated for the existing Woodrow Wilson Bridge by using the E-SRICOS method and the S-SRICOS method and compared with measured scour depths. A scour analysis for the replacement bridge was also performed by using the S-SRICOS method for the design floods.

1. As shown by the results of the EFA tests, the scour rate of the soil samples taken from the bridge site is relatively high, however the critical shear stress is also relatively high. The EFA results confirm that the correlations between soil erodibility and soil properties are very weak at best.
2. In all cases, the measured and the predicted final scour depths did not reach the maximum predicted scour depth $z_{max}$ even though the bridge life is about 39 years. The average predicted final scour depth for all piers was 66% of the average predicted maximum scour depth. This is an indication of the margin of safety that existed for that bridge.
3. A high velocity flood does not greatly contribute to the scour depth in erosion resistant cohesive soils when a certain amount of scour depth has already been developed. The scour depth development in cohesive soils tends to be much more gradual than in cohesionless soils and therefore allows more time for inspection and maintenance.
4. Both of the E-SRICOS and the S-SRICOS methods gave reasonable predictions for the existing Woodrow Wilson Bridge. The simple SRICOS (S-SRICOS) method correlates well with the extended SRICOS (E-SRICOS) method.
5. The HEC-18 equation gave predicted scour depths larger than the final scour depths predicted by the SRICOS method.
6. A factor of safety should be used on the predicted scour depth to minimize the risk of having an actual scour depth much larger than the predicted one.

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