Conference Paper, Published Version

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The SRICOS-EFA Method

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ABSTRACT

The SRICOS-EFA method is used to predict the scour depth versus time curve for complex pier and contraction scour in soils including sands, silts, clays, and soft rock. It consists of taking soil samples at the site, testing them in the EFA (Erosion Function Apparatus), and using the results as input to the SRICOS computer program. A hand calculation version of the method for preliminary design purposes also exists. The method is presented and comparisons between predictions and measurements at full scale are shown. A new approach to predict future hydrographs and perform risk evaluation is included.

SOIL CATEGORIES

Soils can be defined as loosely bound to unbound naturally occurring materials which cover the top few hundred meters of the Earth. By opposition, rock is a strongly bound naturally occurring material found within similar depths or deeper. At the boundary between soils and rocks are intermediate geo-materials. Classification tests and mechanical properties help to distinguish between those three types of naturally occurring materials and between different categories of soils. For soils, the classification tests consist of grain size analysis and Atterberg limits (Das, 2001). The D_{50} grain size is the grain size corresponding to 50% by weight of the soil passing a sieve of opening equal to D_{50}. The first major division in soils classification is between large-grained soils and fine-grained soils; large-grained soils have D_{50} larger than 0.075mm while fine-grained soils have D_{50} smaller than 0.075mm. Large-grained soils include gravels and sands which are identified on the basis of their grain size. Fine grained soils include silts and clays which are identified on the basis of Atterberg Limits. Large grained soils are typically referred to as cohesionless soils while silts and clays are typically referred to as cohesive soils.

ERODIBILITY: A DEFINITION

Erodibility is a term often used in scour and erosion studies. Erodibility may be thought of as one number which characterizes the rate at which a soil is eroded by the flowing water. With this concept erosion resistant soils would have a low erodibility index and erosion sensitive soils would have a high erodibility index. This concept is not appropriate; indeed the water velocity can vary drastically in rivers from 0 m/s to 5 m/s or more and therefore the erodibility is a not a single number but a relationship between the velocity applied and the corresponding erosion rate experienced by the soils. While this is an improved definition of erodibility, it still presents some problems because water

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velocity is a vector quantity which varies everywhere in the flow. It is much preferable to quantify the action of the water on the soil by using the shear stress applied by the water on the soil at the water-soil interface. Erodibility is therefore defined here as the relationship between the erosion rate $\dot{z}$ and the hydraulic shear stress applied □ (Figure 1). This relationship is called the erosion function $\dot{z}$(□). The erodibility of a soil or a rock is represented by the erosion function of that soil or rock

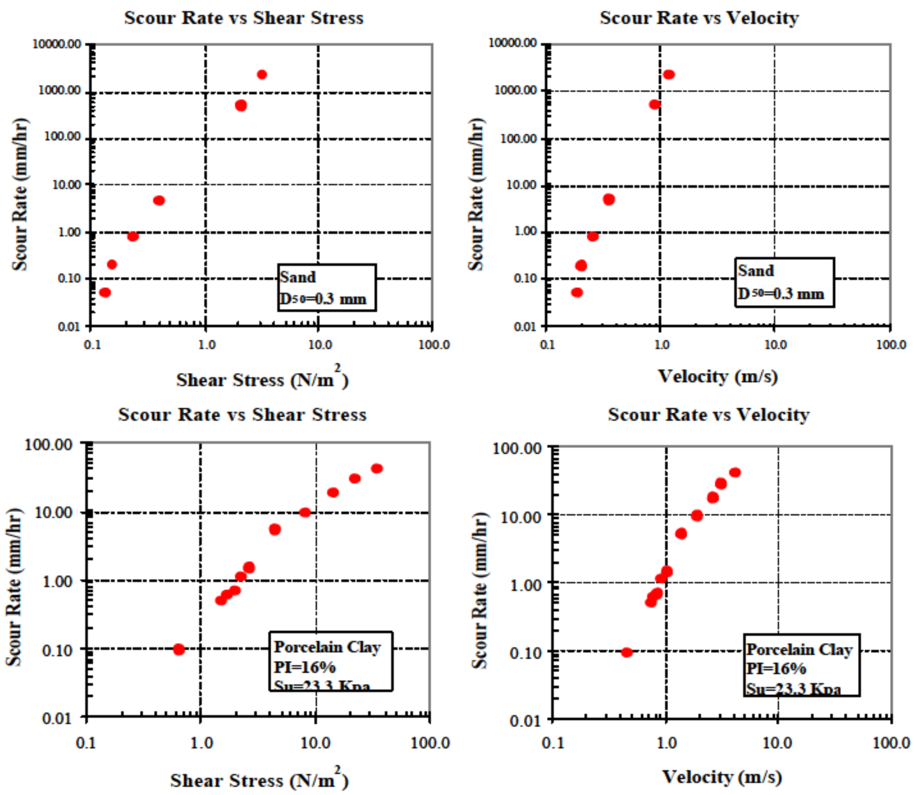


Fig. 1: Example of Erodibility Functions

THE EFA: EROSION FUNCTION APPARATUS

The EFA or Erosion Function Apparatus (Figures 2 and 3) (Briaud et al. 1999, 2001a) (http://www.humboldtmfg.com/pdf2/hm4000ds.pdf , http://tti.tamu.edu/geotech/scour) was conceived in 1991, designed in 1992, and built in 1993. The sample of soil, fine-grained or not, is taken in the field by pushing an ASTM standard Shelby tube with a 76.2 mm outside diameter (ASTM D1587) or by coring a soft rock sample (ASTM D2113). One end of the sampling tube full of soil or soft rock is placed through a circular opening in the bottom of a rectangular cross section conduit. A snug fit and an O-ring establish a leak proof connection. The cross section of the rectangular conduit is 101.6 mm by 50.8 mm. The conduit is about 1 m long and has a flow straightener at one end. The water is driven through the conduit by a pump. A valve regulates the flow and a flow meter is used to measure the flow rate. The range of mean flow velocities is 0.1 m/s to 6 m/s. The end of the sampling tube is held flush with the bottom of the rectangular conduit. A piston at the bottom end of the sampling tube pushes the soil until it protrudes 1 mm into the rectangular conduit at the other end. This 1 mm protrusion of soil is eroded by the water flowing over it. The test measurements consist of the discharge from the flow meter and the time required for eroding the 1 mm protrusion. Several velocities are used and for each velocity, the erosion rate is measured. The data reduction consists of calculating the erosion rate $\dot{z}$ and the shear stress τ at the soil water interface. The shear stress is obtained from the velocity by using Moody's chart for pipe flow. The details are in Briaud et al.(2001a). The result of an EFA test is the erosion function (Figure 1). Over the years, a database of about 100 erosion functions on different soils and soft rocks has been accumulated at Texas A&M University. Repeated attempts at correlating some of the parameters describing the erosion function to basic soil properties failed to yield R^2 values higher than about 0.1 (Briaud et al., 2002). Therefore even if the concept of erodibility index was valid, it is very unlikely that a simple correlation with basic soil or soft rock properties exists.

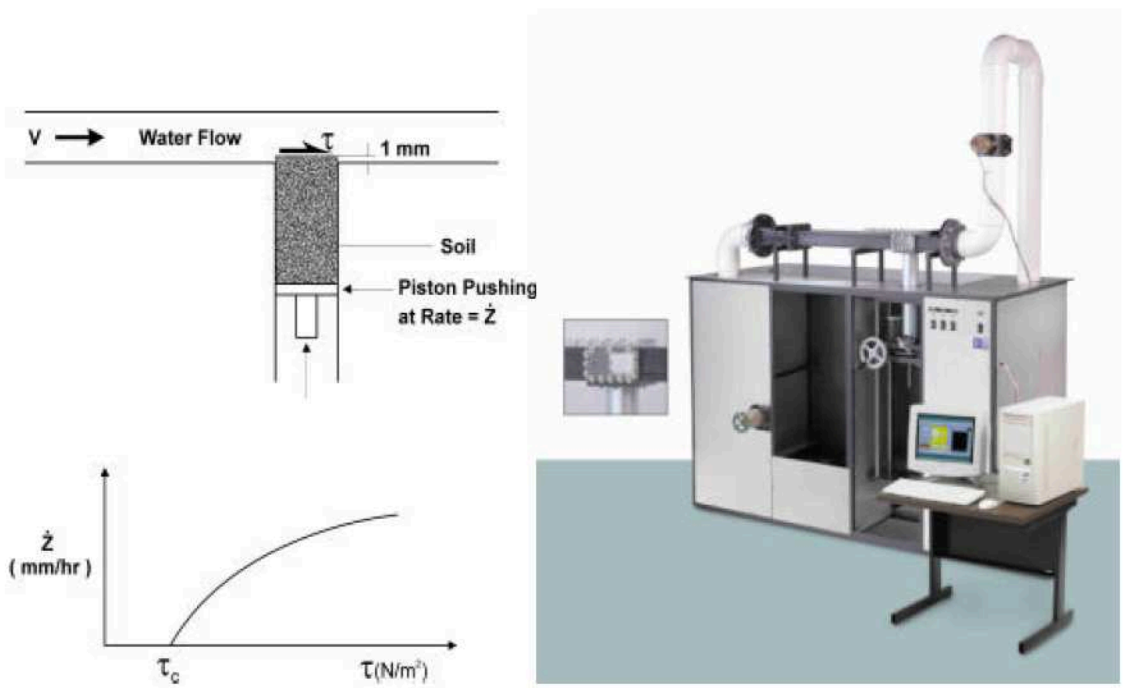


Fig. 2: Schematic Diagram, Result, and Photo of the EFA (Erosion Function Apparatus)

THE SRICOS-EFA METHOD

Now that the erodibility function or erosion function is obtained on a site specific basis with the EFA it is possible to use it to predict the scour depth versus time curve. In cohesionless soils, it is usually sufficient to calculate the maximum scour depth due to the design flood. Indeed, the scour rate in cohesionless soils is fast enough that one flood is long enough to generate the maximum scour depth for that velocity. This is rarely the case in cohesive soils and in rocks where only a fraction of the maximum scour depth may occur during the design flood. In cohesive soils and in rocks it can be very advantageous to predict the scour depth vs. time curve because ignoring it can be very conservative and costly. Ignoring the rate of erosion effect in cohesive soils may lead to unnecessarily deeper and more expensive foundations. An example of the difference

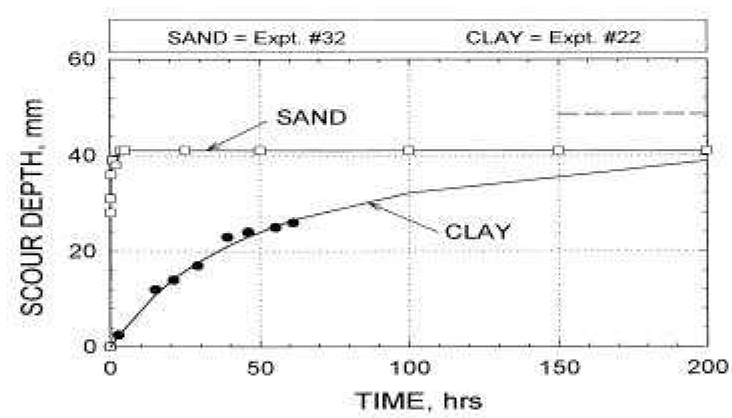


Fig. 3: Comparison between scour rate in sand and in clay for two flume experiments

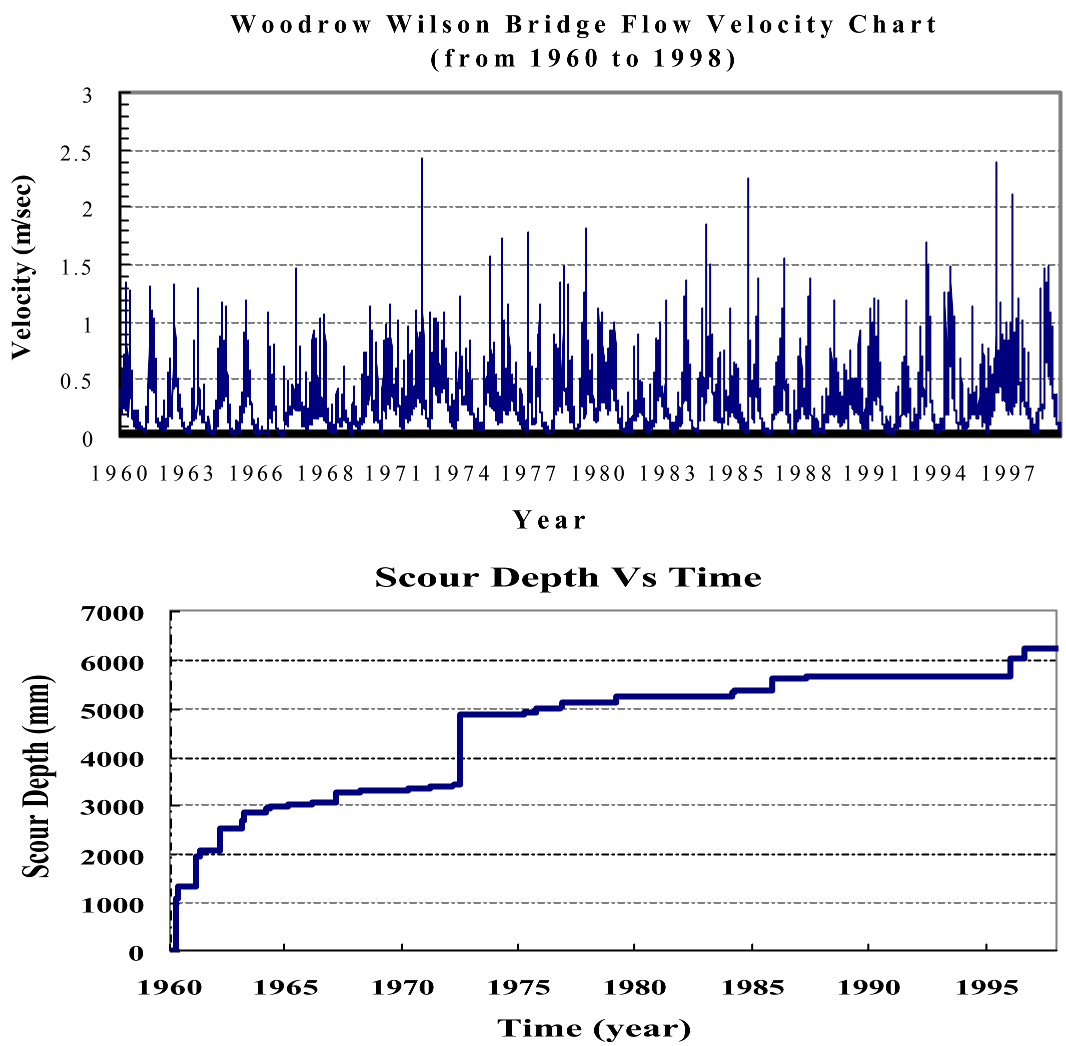


Fig. 4: Example of Output generated by the SRICOS-EFA Program.

between a scour depth versus time curve in a cohesionless soil and a cohesive soil is shown in Figure 3.

Figure 3 shows the scour depth vs. time curve for a constant velocity; however in reality the mean depth velocity in a river (Figure 4) varies significantly during the life of a bridge. The SRICOS-EFA method (Briaud et al., 2001b) was developed to predict the scour depth vs. time curve for bridges subjected to a varying velocity-time history in a layered soil or soft rock. The method can handle pier scour, contraction scour and the combination of the two occurring simultaneously. The solution for abutment scour is under development. The pier scour prediction includes circular and rectangular piers, shallow and deep water depth, different angles of attack, and the effect of pier spacing. The contraction scour prediction includes the effect of the contraction ratio, the length of the contracted channel, the water depth, and the transition angle.

The method consists of the following steps (Briaud et al., 2002):

1. Collect the input data: velocity and water depth hydrograph, geometry of the pier and of the contracted channel, erosion functions of the soil layers.
2. Calculate the maximum contraction scour depth for the i^{th} velocity in the hydrograph.
3. Calculate the maximum complex pier scour depth using the i^{th} velocity in the hydrograph at the pier location if there is no contraction scour in step 2, or the critical velocity for the soil if there is contraction scour in step 2.
4. Calculate the total pier scour depth as the total of step 2 and step 3.
5. Calculate the initial maximum shear stress for pier scour using the i^{th} velocity in the hydrograph.
6. Read the initial scour rate corresponding to the initial maximum shear stress of step 5 on the erosion function of the soil layer corresponding to the current scour depth.
7. Use the results of steps 4 and 6 to construct the hyperbola describing the scour depth vs time for the pier.
8. Calculate the equivalent time for the given curve of step 7. The equivalent time is the time required for the i^{th} velocity on the hydrograph to scour the soil to a depth equal to the depth scoured by all the velocities occurring prior to the i^{th} velocity.
9. Read the additional scour generated by the i^{th} velocity starting at the equivalent time and ending at the equivalent time plus the time increment.
10. Repeat steps 2 to 9 for the (i+1)th velocity and so on until the entire hydrograph is consumed.

The equations for the maximum scour depth values were developed on the basis of flume tests while the equations for the initial shear stress were developed from numerical simulations. The accumulation algorithms for velocity history and layering systems were constructed by using the concept of an equivalent time. Care was taken not to simply add the pier scour depth and the contraction scour depth. The details of the method as well as the manual for the SRICOS-EFA program can be found in Briaud et al. (2002). A simplified version of the method was also developed for preliminary design purposes. An example of that method is shown in Figure 5.

Problem: *Maximum flood velocity = 3 m/s*
Bridge design life = 75 years
Pier diameter = 2 m
Water depth = 5 m
What is the depth of scour after 75 years?

Solution: *S-SRICOS Method*

1. *Results of EFA tests gave the $\dot{z}$ vs τ curve shown.*
2. *Maximum hydraulic shear stress around the pier is:*

   $$\tau_{max} = 0.094\ \rho v^2 \left(\frac{1}{logRe} - \frac{1}{10} \right) = 40\ N/m^2$$

3. *The initial rate of scour $\dot{z}_i$ is read on the EFA curve at $\tau = \tau_{max}$. $\dot{z}_i = 6$ mm/hr*
4. *The maximum depth of scour z_{max} is*

   $$z_{max} = 0.18\ Re^{0.635} = 3626\ mm$$

5. *Equivalent time*

   $$t_e = 73 (t_{hydro})^{0.126} (v_{max})^{1.706} (\dot{z}_i)^{-0.2} = 573\ hrs.$$

6. *The equation for the $z(t)$ curve is*

   $$z = \frac{t}{\frac{1}{\dot{z}_i} + \frac{t}{z_{max}}} = 1765\ mm \text{ after 75 years}$$

   $z_{75\ years}$ *is 49% of* z_{max}

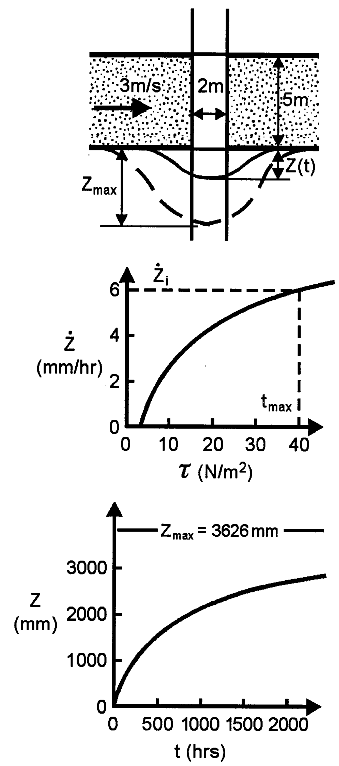
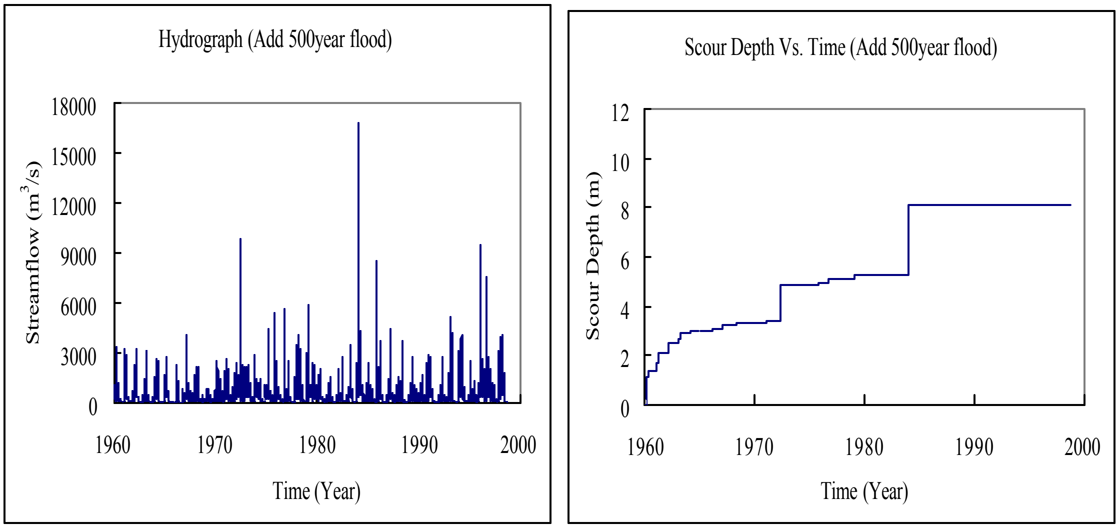


Fig. 5: Example of scour calculations by the simplified SRICOS-EFA method.

FUTURE HYDROGRAPHS AND SCOUR RISK ANALYSIS

Since the SRICOS-EFA method predicts the scour depth as a function of time, one of the input is the velocity versus time curve or hydrograph at the foundation location. This hydrograph should cover the period over which the scour depth must be predicted. A typical bridge is designed for 75 years. Therefore the design for a new bridge requires the knowledge of the hydrograph from the year of construction until that year plus 75 years. The question is: how can one obtain the future hydrograph covering that long period of time? This requires predicting the future over a 75-year period!

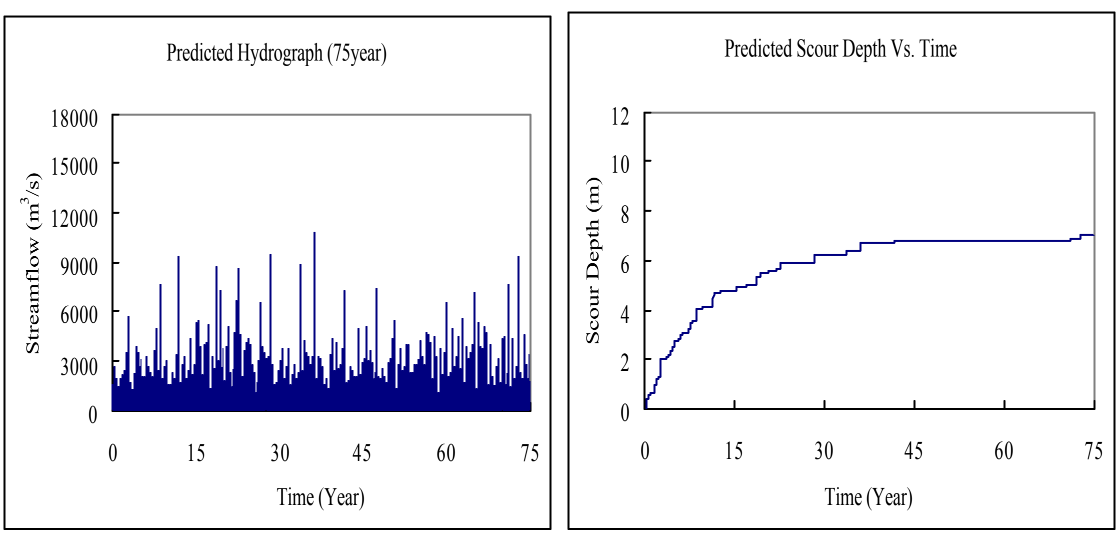
One solution is to use a hydrograph recorded at a nearby gauge station over the last 75 years and assume that the future hydrograph will be equal to the past hydrograph. If the gauge is not at the future bridge location, the discharge can be multiplied by the ratio of the drainage area at the bridge site over the drainage area at the gauge site. If the record at the gauge station is not 75 years long, one can simply repeat the recorded hydrograph until it covers the 75-year period. If the recorded hydrograph does not include the design flood (100 year flood or 500 year flood), one can spike the hydrograph with one or more of those floods before running the SRICOS program (Figure 6).



(a) Hydrograph (b) Scour Depth Vs. Time Curve

Fig. 6: Woodrow Wilson Measured Hydrograph spiked with a 500-year Flood

Another approach (Briaud, D'Odorico, 2002) consists of using a past hydrograph, preparing the frequency distribution plot for the floods within that hydrograph, sampling the distribution randomly and preparing a future hydrograph, for the required period, which has the same mean and standard deviation as the measured hydrograph (Figure 7). This process is repeated 10,000 times and, for each hydrograph, a final scour depth (the depth reached after 75 years of flow) is generated. These 10,000 final depths of scour are organized in a frequency distribution plot with a mean and a standard deviation. That plot can be used to quote a scour depth with a corresponding probability of occurrence, or better, to choose a risk level and quote the corresponding final depth of scour (Figure 8).



(a) Hydrograph (b) Scour Depth vs. Time

Fig. 7: Predicted Hydrograph and Scour Depth vs. Time Curve at Woodrow Wilson Bridge Site (Project time = 75year)

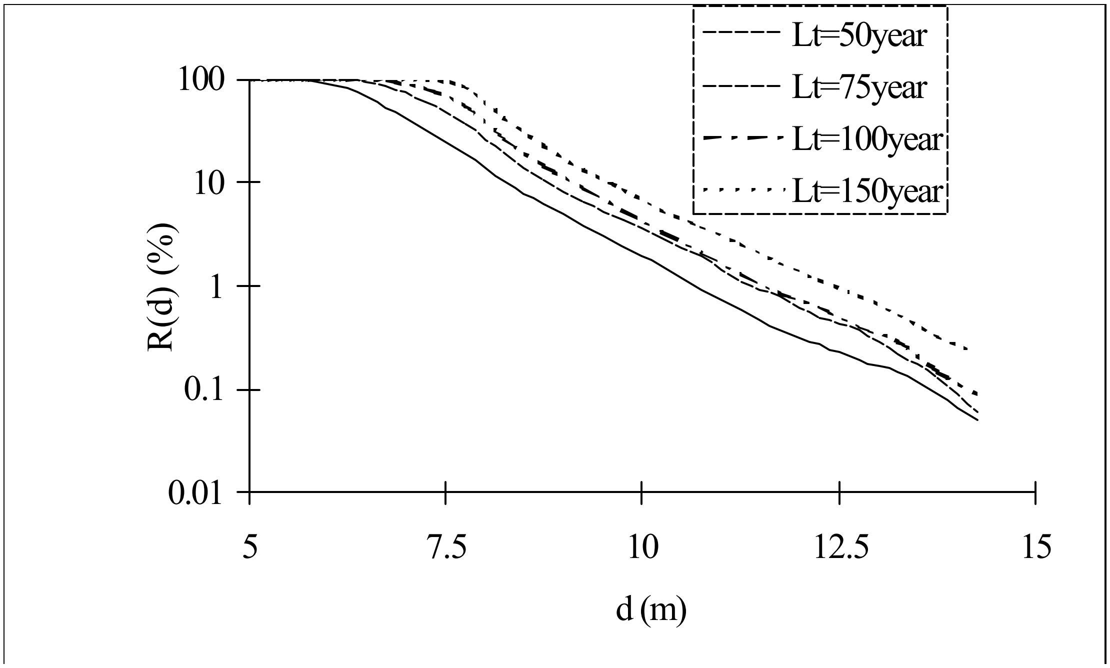


Fig. 8: Risk associated with different design values of the final scour depth, *d*, and different lengths of the project life, L_t

OBSERVATIONS ON CURRENT RISK LEVELS

In current design practice, the 100 year flood and the 500 year flood are used. If the design life of the bridge is L_t, the probability of exceedence or risk R for a flood having a return period T_r is given by:

$$R = 1 - (1 - 1/Tr)^{Lt} \quad (1)$$

If the design life of the bridge is 75 years, the probability that the flood with a return period of 100 year will be exceeded during the 75 year design life is 53% according to equation 1. Therefore the risk that the 100 year flood will be exceeded during the 75 years is 53% or about one chance out of two. For the 500 year flood, and for the same 75 year design life, the risk is 14% or one chance in about seven.

Even if a bridge designed for a 100 or 500 year flood experiences a 1000 year flood, this bridge may not collapse. Indeed collapse of the bridge is based on a different criterion than just exceedence of the design flood. There are numerous inherent redundancies in the design of a bridge and many design parameters have to be exceeded before collapse occurs. Nevertheless, the risk level associated with the floods used in everyday design appears very high compared to risk levels in other disciplines within Civil Engineering. For example the structural engineers have based their codes on a risk level of about 0.1%. The geotechnical engineers probably operate at about 1%. The scour engineers seem to operate at a much higher risk level. This is particularly worrisome since there is no factor of safety on the depth of scour passed on from the scour engineer to the geotechnical engineer for him to calculate the pile length.

VERIFICATION OF THE SRICOS-EFA METHOD

In order to evaluate the SRICOS-EFA method, 8 bridges were selected in Texas. These bridges all satisfied the following requirements: the predominant soil type was fine grained soils according to existing borings, the river bottom profiles were measured at two dates separated by at least several years, these river bottom profiles indicated anywhere from 0.05m to 4.57m of scour, a USGS gaging station existed near the bridge, and drilling access was relatively easy. The data for all bridges is listed in Tables 1 and 2.

For each bridge, Shelby tube samples were retrieved, tested in the EFA and the SRICOS-EFA method was used to predict the local scour at the chosen bridge pier location. One pier was selected for each bridge except for the Navasota River bridge at SH7 and the Trinity River bridge at FM787 for which two piers were selected. Therefore a total of 10 predictions were made for these 8 bridges. These predictions are not Class A predictions since the measured values were known before the prediction process started. However the predictions were not modified once they were obtained. The results are shown in Figure 9 and indicate a good comparison.

In addition to this verification process, the SRICOS-EFA method was compared to the to the HEC-18 method (Richardson, Davis, 2001) for complex pier scour using the data base developed by Mueller (1996). The results are shown on Figure 10 and 11. The good and safe comparison obtained for this predominently cohesionless soils database and the similarity of results with the HEC-18 method indicates that the range of applications of the SRICOS-EFA method is not limited to cohesive soils. One might ask: If the SRICOS-EFA method gives the same results as the HEC-18 method why do we need the SRICOS-EFA method? The answer is that the HEC-18 method cannot predict the rate of scour while the SRICOS-EFA method can. It is however reassuring to see that the SRICOS-EFA method is consistent with the HEC-18 method when it comes to the maximum depth of scour.

CONCLUSIONS

The SRICOS-EFA method was developed starting in 1991 and has matured over the last 11 years. The method makes use of the SRICOS computer program. A hand calculation version of the method also exists. The SRICOS-EFA method can handle the prediction of the scour depth versus time curve for complex piers and for contraction scour where the soil is sand, silt, clay, or soft rock. It has been verified against full-scale case histories and against large databases. The SRICOS-EFA method for abutment scour is being developed.

Table 1: Full Scale Bridges as Case Histories

Bridge	Pier Bent No.	Pier Width (m)	Pier Length (m)	Pier Shape	Skew Angle (°)	River Slope	Manning's Coefficient n	Max. Velocity (m/s)	True Duration of Hydrograph (yrs)
Navasota River at SH 7	3	0.36	0.36	Square	5	0.0010	0.035	2.54	41
Navasota River at SH 7	5	0.36	8.53	Square Nose	5	0.0010	0.035	3.82	41
Brazos River at US 90A	3	0.91	8.53	Round Nose	0	0.0011	0.035	4.20	33
San Jacinto River at US 90	43	0.85	0.85	Square	15	0.0012	0.035	3.07	10
Trinity River at FM 787	3	0.91	7.30	Round Nose	25	0.0011	0.035	2.00	17
Trinity River at FM 787	4	0.91	7.30	Round Nose	25	0.0011	0.035	4.06	17
San Marcos River at SH 80	9	0.91	14.2	Round Nose	0	0.0010	0.035	1.89	60
Sims Bayou at SH 35	3	0.76	0.76	Circular	5	0.0001	0.035	0.95	3
Bedias Creek at US 75	26	0.86	0.86	Square	0	0.0005	0.035	2.19	50
Bedias Creek at SH 90	6	0.38	0.38	Square	5	0.0010	0.035	1.54	18

Bridge	Distance between Pier and Boring (m)	Max. Shear Stress (N/m2)	Initial Erosion Rate (mm/hr)	Equivalent Time (hrs)	Predicted Local Scour (m)		Measured Local Scour (m)	Measured Total Scour (m)	Predicted Max. Local Scour (m)
					E-SRICOS	S-SRICOS			
Navasota River at SH 7	6.5	41.46	8.91	368.8	0.76	0.82	0.76	-	1.10
Navasota River at SH 7	16.1	86.53	22.39	616.0	1.24	1.29	1.41	1.80	1.42
Brazos River at US 90A	55.4	85.86	65.26	568.4	2.59	2.54	2.87	4.43	2.72
San Jacinto River at US 90	146.3	49.62	17.44	373.1	1.30	1.66	1.47	3.17	2.14
Trinity River at FM 787	37.8	22.46	50.60	155.1	1.53	1.40	2.17	4.57	1.70
Trinity River at FM 787	78.4	80.93	39.82	544.6	2.26	2.37	2.17	4.57	2.66
San Marcos River at SH 80	57.3	20.30	61.75	158.4	1.07	1.40	1.27	2.66	1.64
Sims Bayou at SH 35	20.0	26.71	2.69	63.0	0.29	0.14	0.05	-	0.95
Bedias Creek at US 75	33.0	16.31	127.44	172.5	1.66	1.61	1.35	2.13	1.74
Bedias Creek at SH 90	2.9	5.92	44.25	102.8	0.70	0.70	0.61	-	0.83

Table 2: Soil Properties at the Bridge Sites

Soil Properties	Navasota		Brazos	San Jacinto			Sims
Layer No.	1	2	1, 2	1, 2	3	4	1
Depth (m)	1.8–2.4	4.9–5.5	13.0–13.7	5.3-6.1	6.9-7.6	7.6-8.4	3.0-3.7
Liquid Limit (%)	27.72	26.42	24.49	22.04	-	37.50	84.16
Plastic Limit (%)	14.29	6.25	9.41	9.09	-	12.71	16.05
Plasticity Index (%)	13.43	20.17	15.08	12.95	-	24.79	68.11
Water Content (%)	19.80	26.60	17.32	151.57	26.88	27.75	25.25
Mean Diameter, D_{50} (mm)	0.125	-	0.265	-	-	-	0.0012
Shear Strength (kPa)	43.10	32.10	45.49	23.94	4.78	21.53	23.00
Unit Weight (kN/m^3)	19.20	18.80	20.20	19.60	16.70	20.80	19.60
% Passing #200 Sieve	26.20	57.70	30.09	50.36	60.71	94.50	99.07

Soil Properties	Trinity		San Marcos		Bedias 75		Bedias 90
Layer No.	1	2	1	2	1	2	1
Depth (m)	10.7-11.4	13.0-13.7	6.1-6.6	7.0-7.5	6.1-6.9	6.9-7.6	1.5-2.3
Liquid Limit (%)	-	42.24	41.34	40.31	47.86	-	55.08
Plastic Limit (%)	-	8.70	16.67	19.18	13.56	-	15.79
Plasticity Index (%)	-	33.54	24.67	21.13	34.30	-	39.29
Water Content (%)	7.67	22.22	22.00	24.40	18.07	17.50	23.63
Mean Diameter, D_{50} (mm)	6.00	-	-	-	0.048	0.130	0.040
Shear Strength (kPa)	9.57	11.48	27.30	29.67	10.00	32.00	62.00
Unit Weight (kN/m^3)	22.00	22.10	19.60	20.20	20.04	21.30	19.60
% Passing #200 Sieve	11.52	68.40	78.30	73.40	86.81	35.14	91.31

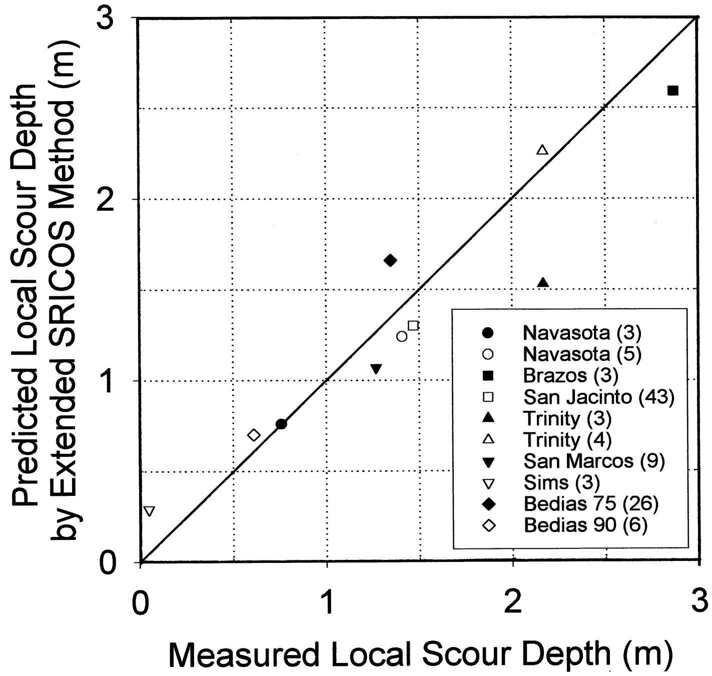


Fig. 9: Predicted vs Measured Local Scour for the E-SRICOS method.

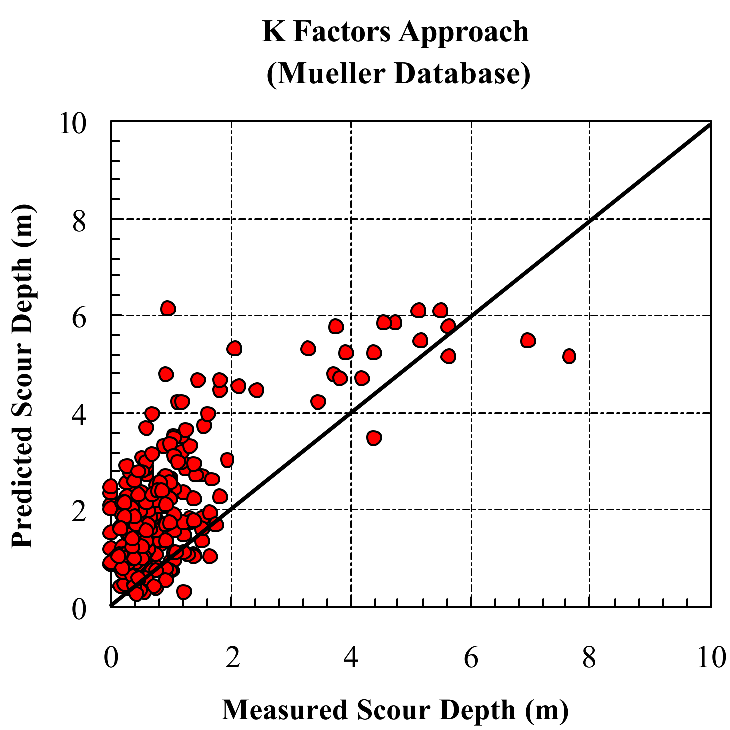


Fig. 10: SRICOS-EFA Predictions against Mueller (1996) Database

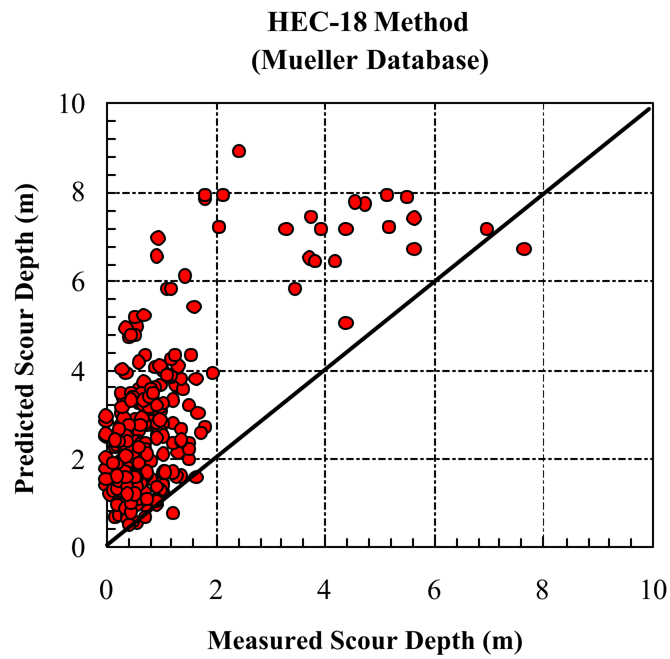


Fig. 11: HEC-18 Predictions against Mueller (1996) Database

ACKNOWLEDGEMENTS

Many organizations and individuals have contributed to the development of the SRICOS-EFA method. They are all thanked sincerely. Texas DOT, NCHRP, Maryland SHA, North Carolina DOT, Minnesota DOT, Illinois DOT, Texas Transportation Institute, Humboldt, H.-C. Chen, Francis Ting, Ya Li, Jun Wang, Prahoro Nurtjahyo, Kiseok Kwak, Yiwen Cao, Seung-Woon Han, Rao Gudavalli, Suresh Perugu, Gengshen Wei, Peter Smith, Tony Schneider, Melinda luna, Kim Culp, Jay Vose, Mark McClelland, John Delphia, Andy Kosicki, Stan Davis, John Boynton, Ryhad Wahad, Bill Moore, Steven Smith, Larry Arneson, Daryl Greer, Robert Henthorne, Rochard Phillips, Mehmet Tumay, Sterling Jones, Tim Hess, Mahir Al-Nadaf.

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