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Future Hydrographs and Scour Risk Analysis

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ABSTRACT

The SRICOS-EFA method is used to predict the scour depth versus time curve for bridge pier scour and/or contraction scour in soils. The input for this method consists of the velocity hydrograph to which the pier will be subjected, the geometry of the pier and the channel, and the soil erodibility function for the soils to be eroded. The velocity hydrograph required for the design of a new bridge describes the mean depth velocity of the water at the location of the pier as a function of time for the design life of the bridge, say 75 years. A new procedure is presented to generate possible future hydrographs. This new procedure makes it simple to give the scour depth results in terms of risk levels.

THE SRICOS-EFA METHOD

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

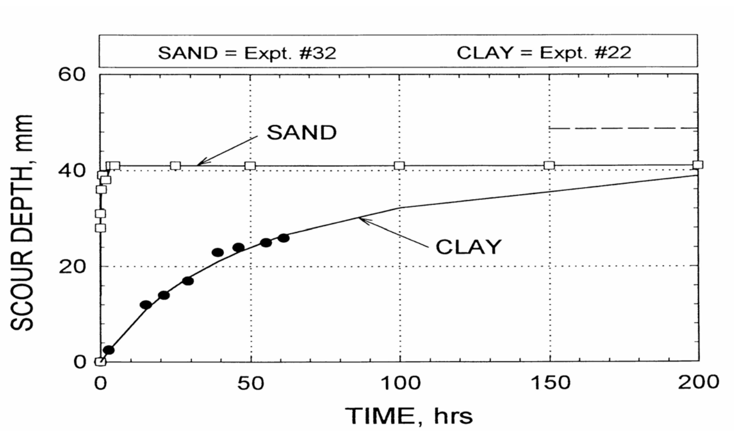

Fig. 1: Comparison between scour rate in sand and in clay for two flume experiments

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between a scour depth versus time curve in a cohesionless soil and a cohesive soil is shown in Figure 1.

Figure 1 shows the scour depth vs. time curve for a constant velocity; however in reality the mean depth velocity in a river (Figure 2) varies significantly during the life of a bridge. The SRICOS-EFA method (Briaud et al., 1999, 2001a, 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.

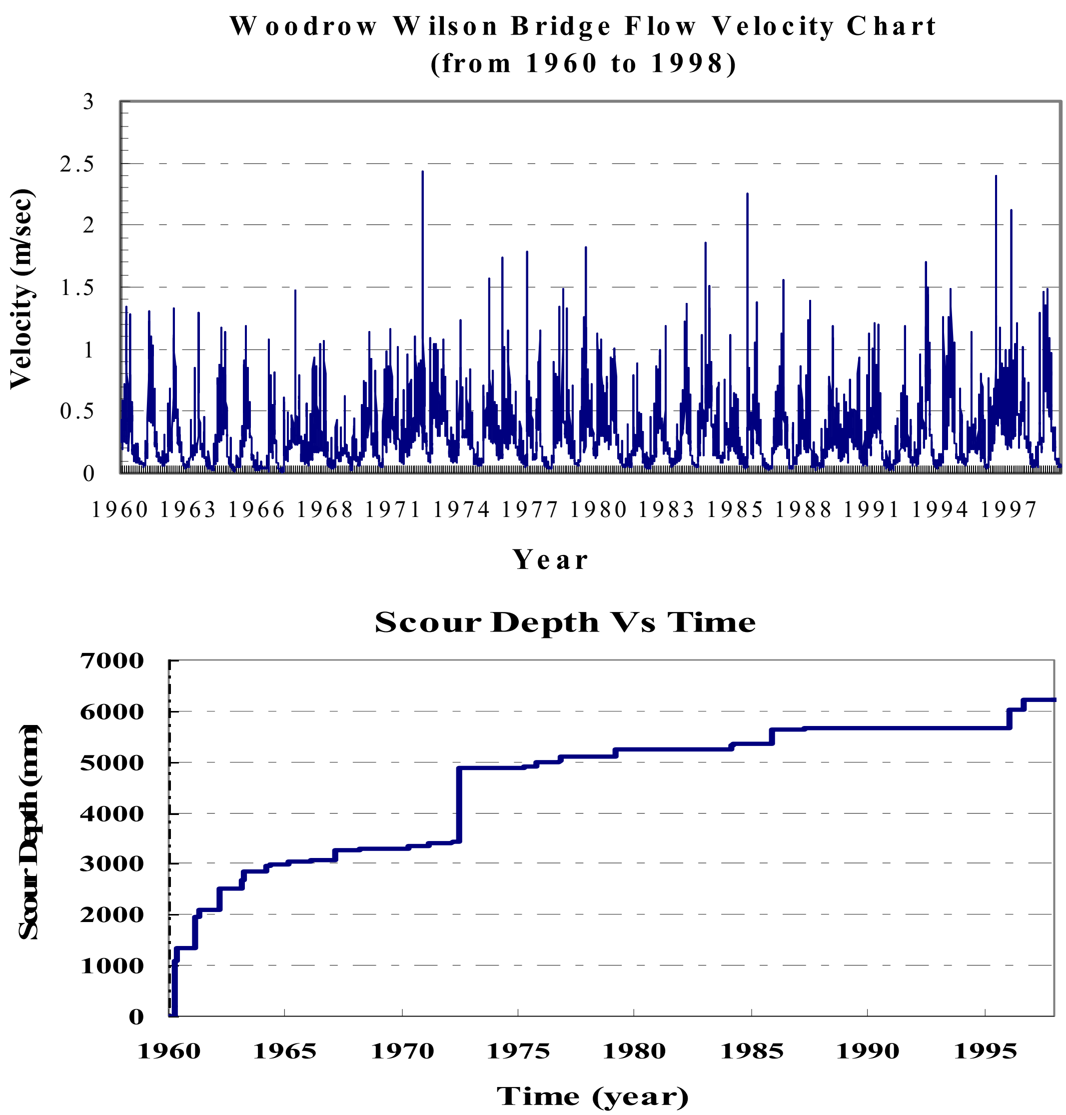


Fig. 2: Example of Output generated by the SRICOS-EFA Program.

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

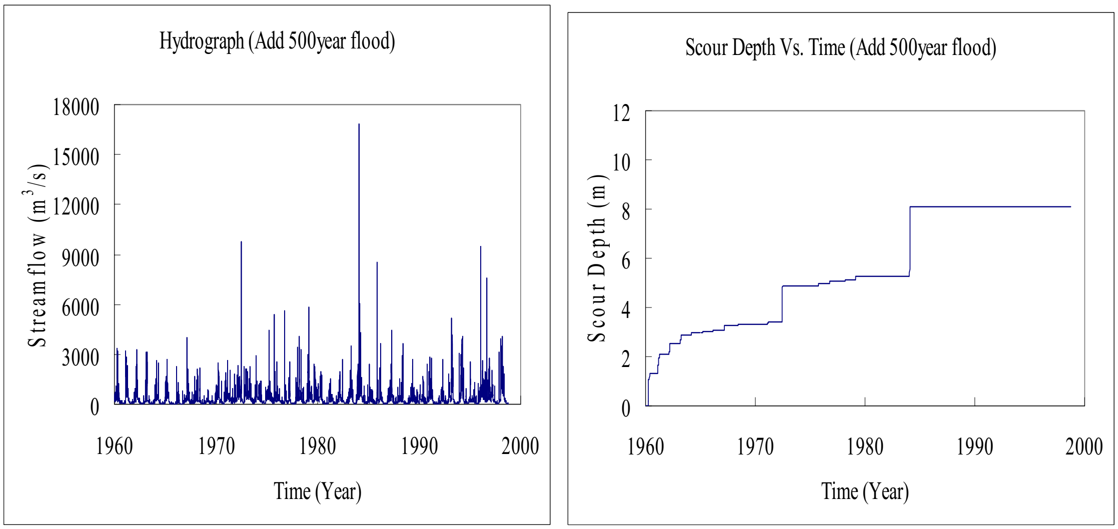
1. Collect the input data: velocity and water depth hydrograph, geometry of the pier and of the contracted channel, erosion functions of the soil layers.
2. Calculate the maximum contraction scour depth for the i^{th} velocity in the hydrograph.
3. Calculate the maximum complex pier scour depth using 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).

USING AN EXISTING HYDROGRAPH

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! The uncertainty inherent to the climatic and hydrologic processes determining the hydrograph characteristics suggests using a statistical approach in the generation of plausible 75-year hydrographs.

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 3).



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

Fig.3: Woodrow Wilson Measured Hydrograph spiked with a 500-year Flood

RANDOMLY GENERATED FUTURE HYDROGRAPHS

Another solution is to use the new technique which is presented here. This technique 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. 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.

The SRICOS-EFA method determines the scour depth at the end of the bridge life as a progressive process driven by a given sequence of daily stream-flow values throughout the life, L_t, of the structure. The randomness of the hydrologic function suggests combining the scour model with some hydrological and statistical analyses. If the stream-flow sequence (or *hydrograph*) is modeled as a stochastic process, it is possible to set up a Monte Carlo procedure sampling from that process different realizations of the hydrograph (of length L_t), and estimating (SRICOS-EFA method) for each of them the scour depth, *d*, at the end of the bridge life. Thus, *d* is regarded as a random variable and its statistics can be studied in detail to determine the risk of failure associated with different choices of the design value of the scour depth.

The modeling of daily stream-flow, *Q*, can be tackled using different approaches (e.g., Bras and Rodriguez-Iturbe, 1986; Montanari et al., 1997; 2000) corresponding to different levels of complexity. A first simple analysis suggested here considers *Q* as a random, uncorrelated variable. A suitable distribution is fitted to the data and the hydrographs are then generated as series of values sampled from such a distribution. Ongoing research is also applying other stochastic models to account for both the autocorrelation and the memory of the process and is assessing whether the temporal structure (i.e. both autocorrelation and memory) of the stream-flow sequences is able to affect the statistical properties of the scour-depth probability distribution.

The theoretical distribution used to model daily stream-flow observations needs to be defined only for positive values of *Q,* to have a positive skewness, and to be able to provide an accurate representation of the extreme values (i.e. good fit at the upper tail of the distribution). As expected, the extreme values are found to greatly affect the scour depth estimates and an imprecise modeling of stream-flow maxima could easily lead to unrealistic estimations of the scour depth statistics. Logarithmic transformations are frequently used to study stream-flow extremes (e.g., Chow et al., 1988; Benjamin and Cornell, 1970); therefore, a log-normal distribution can be a good candidate for modeling the daily stream-flows. The method of moments is used to determine the parameters of the distribution. As such, *Q* is expressed as the exponential of a normally distributed random variable, *y*, with mean

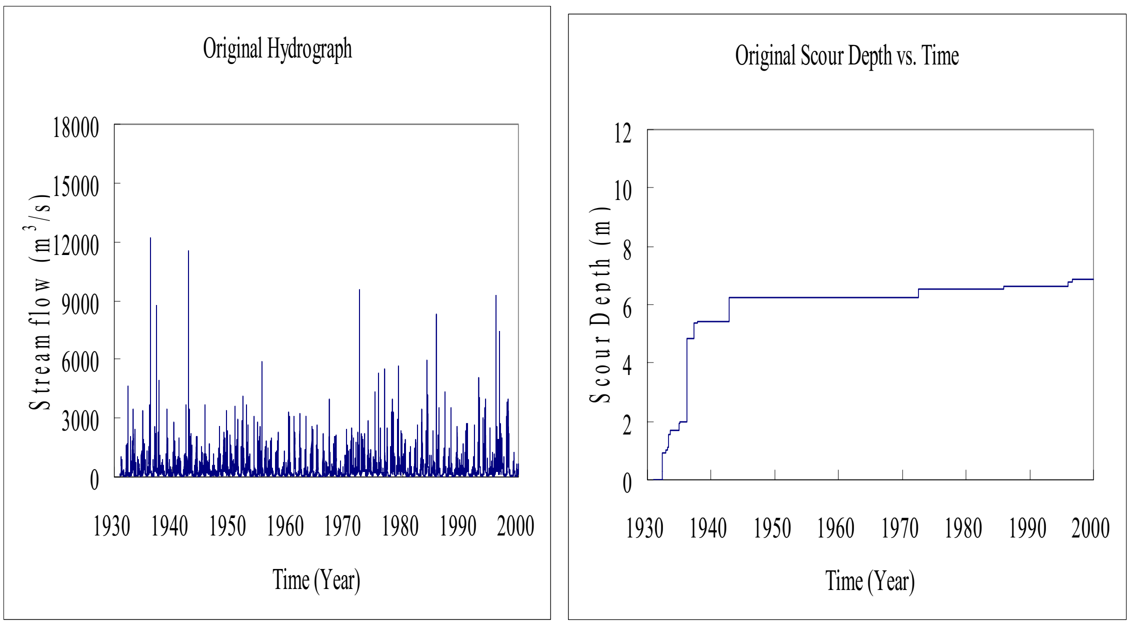
$$\mu_y = \frac{1}{2} Log\left[\frac{\mu_Q{}^2}{1+\left(\frac{\sigma_Q}{\mu_Q}\right)^2}\right] \tag{1}$$

and standard deviation

$$\sigma_y = \sqrt{Log\left[1+\left(\frac{\sigma_Q}{\mu_Q}\right)^2\right]} \tag{2}$$

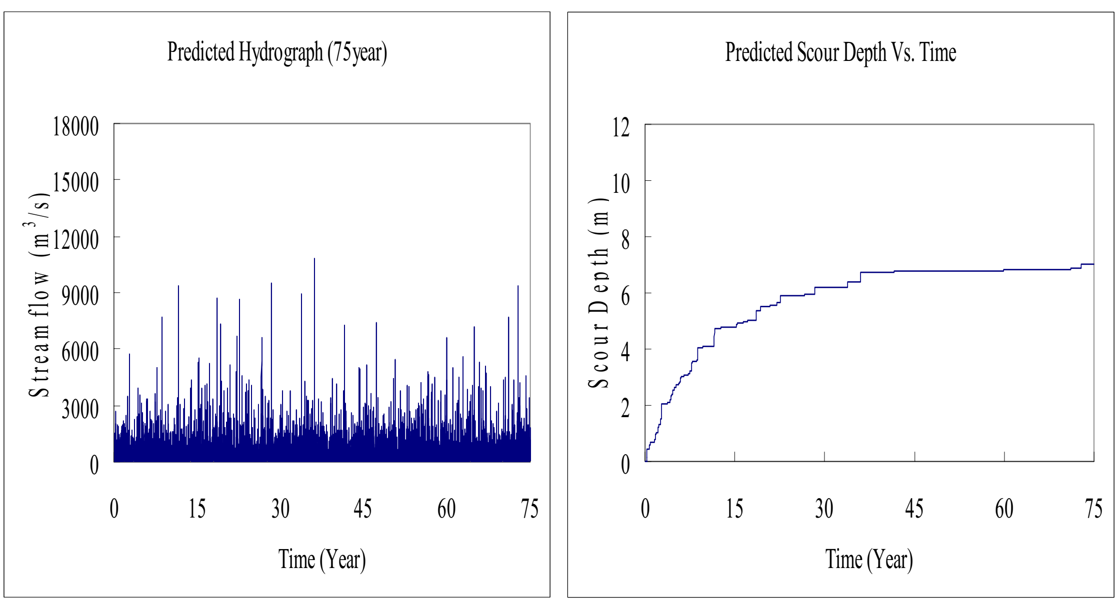
with μ_Q and σ_Q being the mean and the standard deviation of daily stream flow, respectively.

In the case of the Woodrow Wilson Bridge, stream-flow data is available at the Little Falls station (USGS #01646500) on the Potomac River, approximately 13 km upstream from the bridge. Correction of the measured stream flow is applied by multiplying the values by the drainage area ratio. The correction is of the order of 3%. Figure 4 shows the original hydrograph and the corresponding prediction of scour depth history using the SRICOS-EFA method. The mean and standard deviation of *Q* in the period of record 1931-2000 are μ_Q=327 m^3s^{-1}, and σ_Q=467 m^3s^{-1}, respectively, while the maximum discharge in the 70-year-long record was 12,056 m^3s^{-1}. Synthetic hydrographs of the same length generated by sampling from a lognormal distribution of mean μ_Q and standard deviation σ_Q have on the average a maximum value of about 12,000 m^3s^{-1}, suggesting that such a distribution gives an adequate representation of the extrema. Figure 5 shows an example of a generated future hydrograph and the associated scour depth history as predicted by the SRICOS-EFA method.



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

Fig.4: Original Hydrograph & Scour Depth vs. Time near Woodrow Wilson Bridge Site



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

Fig.5: Predicted Hydrograph and Scour Depth vs. Time Curve near Woodrow Wilson Bridge Site (Project time = 75year)

RISK APPROACH TO SCOUR PREDICTIONS

Many equally possible future hydrographs such as the one in Figure 5 are generated by the random sampling process. For each hydrograph, the SRICOS program generates a scour depth history including a final depth of scour, d, at the end of the project life. These values of the final depth of scour can be organized in a frequency distribution. Figure 6 shows the probability distributions obtained for the example of the Woodrow Wilson bridge at the end of a chosen bridge life, L_t.

This analysis can be used to estimate the level of risk, *R*, associated with the choice of different design values of scour depth and project lives. By definition, the risk level is the probability that the design conditions are exceeded in the course of the life of the structure. Thus, from the probability distribution of *d* (Figure 6) it is possible to determine the cumulative distribution function (CDF) of *d* (Figure 7). The risk is then estimated as the probability of exceedence (Figure 7). Table 1 reports the risk level associated with different project lives and design values of *d*. It is observed that *R* is a non-linear function of *d* and L_t. This analysis provides a statistical framework that can be used in a cost-benefit study of bridge foundation design.

Commonly accepted methods of scour analysis in cohesionless soils refer to a single peak-flow value selected on the basis of its return period, T_r, as well as of the associated level of risk. Such an approach does not account for the contribution to bridge scour due to smaller (and more frequent) floods. The SRICOS-EFA method can be used to include the effect of the entire hydrograph. The Monte Carlo procedure outlined in this section represents a possible new probabilistic approach to scour analysis. Ongoing research is developing a extended version of this approach using different stochastic hydrologic models able to account for the daily-flow distribution, and for the autocorrelation of the stream-flow series. This study will show whether the scour depth is sensitive to the temporal structure of stream-flow sequences and will indicate the level of detail that is necessary to include in the hydrologic stochastic model.

OBSERVATIONS ON CURRENT RISK LEVELS

A direct comparison between the risk results obtained here with the SRICOS method (Table 1) and traditional approaches based on single peak-flow values is not easy. Nevertheless, an example is provided here. The peak flow value associated with a given return period can be determined through a flood-frequency analysis (e.g., Chow et al., 1988; pp 375-378). Figure 8 shows the result of such an analysis for the Woodrow Wilson measured hydrograph. As can be seen on that figure, the 100 year flood has a discharge of 12,600 m^3/s and the 500 year flood has a value of 16,600 m^3/s. 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:

$$R = 1 - (1 - 1/Tr)^{Lt} \quad (3)$$

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 3. The risk that the 100 year flood will be exceeded during the 75 years is 53%

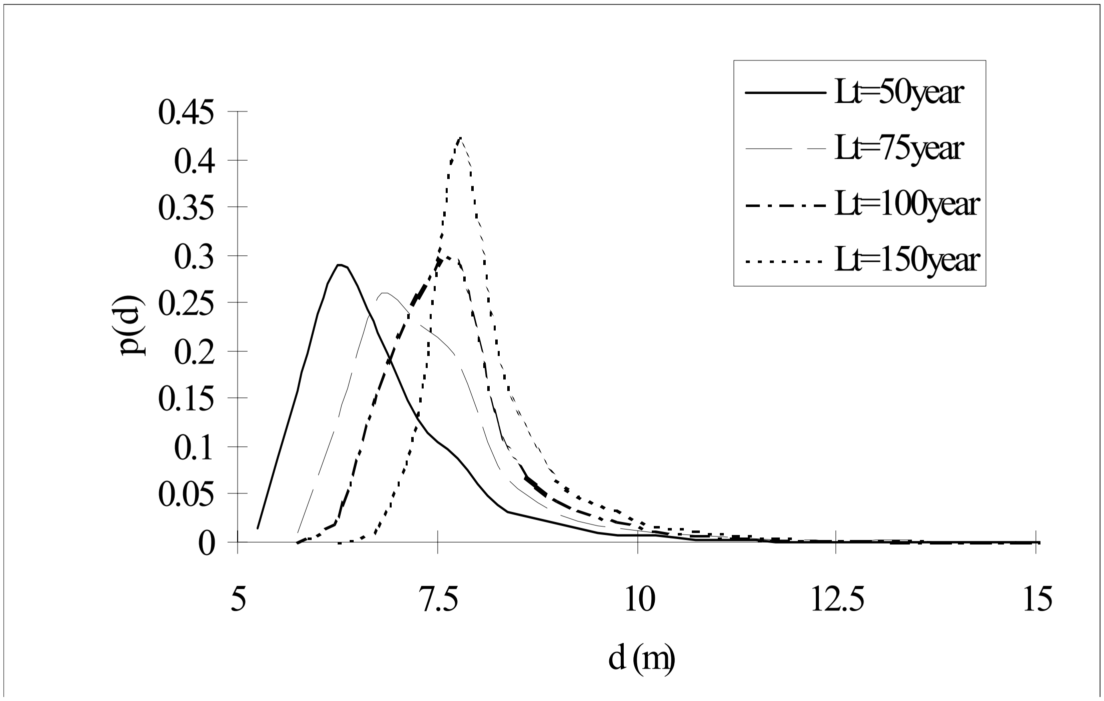


Fig.6: Probability distribution of scour depth, *d*, for different lengths of the project life, L_t

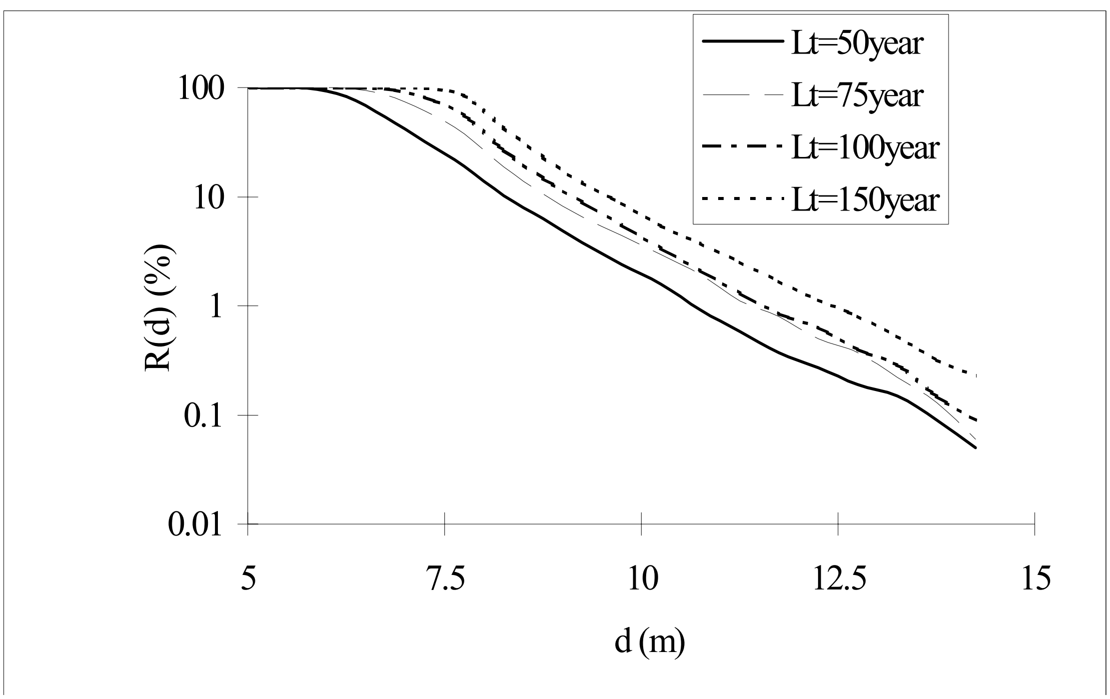


Fig.7: Risk associated with different design values of the final scour depth, *d*, and different lengths of the project life, L_t

Table 1: Risk of failure associated with different design values of scour depth and project lives

Design value of Scour depth (m)	Project Life			
	50 yrs	75 yrs	100 yrs	150 yrs
6.5	42%	74%	91%	99.8%
7.0	25%	48%	70%	93%
7.5	14%	27%	40%	65%

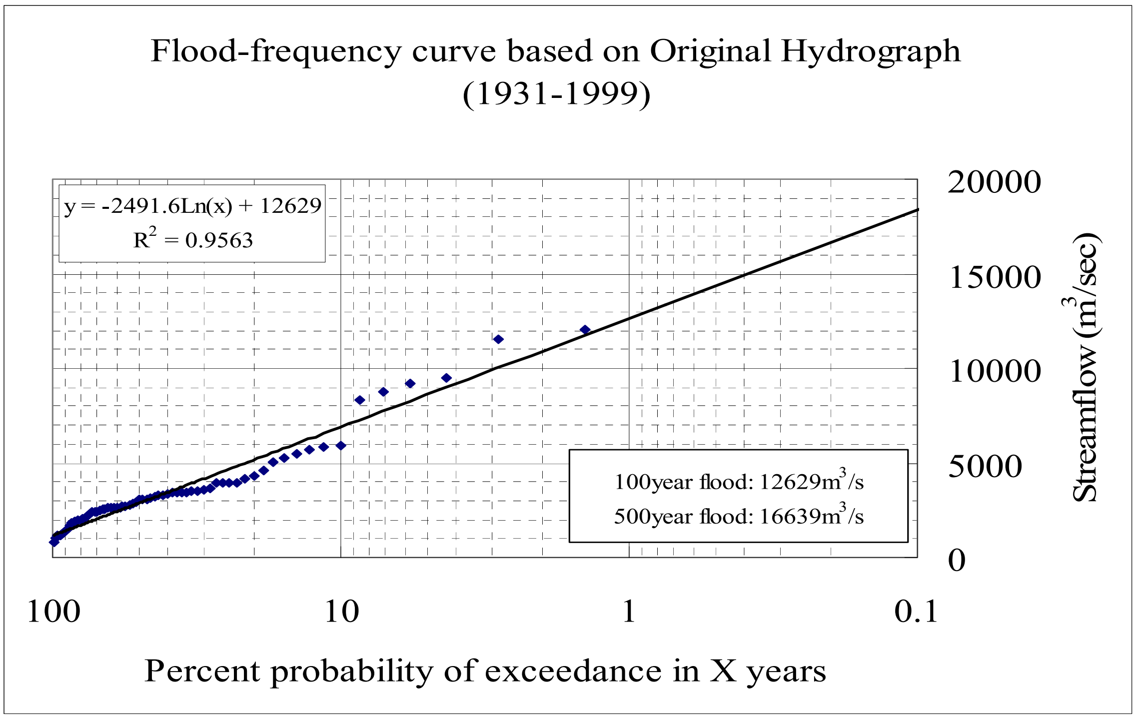


Fig.8: Flood-frequency curve for the Potomac River at the Woodrow Wilson Bridge

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 7.

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.

CONCLUSIONS

The SRICOS-EFA method predicts the scour depth versus time curve for bridge piers. One of the input is the water velocity-time history or hydrograph covering the period over which the bridge is to be designed or evaluated. A new technique to obtain such hydrographs is presented. This technique consists of using a past hydrograph, preparing the frequency distribution plot for the floods within that hydrograph, sampling the distribution randomly and statistically modeling a future hydrograph, for the required period, which has the same mean and standard deviation as the measured hydrograph. 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.

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