UNCERTAINTY EVALUATION IN THE DESIGN OF INSTREAM STRUCTURES FOR STREAM RESTORATION

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Abstract

Many communities have tried to restore urban streams to a more natural condition and to stabilize unstable streams using ecologically friendly methods. A number of procedures have been developed for stream naturalization/restoration. However, considerable uncertainty exists in the application of these procedures particularly with respect to stream stability. Uncertainty analysis has been applied to one design procedure for stream stability design to illustrate its usefulness to improve the design procedure. A procedure used by the Maryland State Highway Administration (MSHA) to check the safety of instream structures used to stabilize streams in stream restoration projects was selected as the example. In this procedure the maximum shear stress in the designed channel computed for the 100-year flow is compared to the critical shear stress for the boulders used to build the structure. If the maximum shear stress is less than the critical shear stress, the structure is considered safe. Uncertainty in Manning's n, the design flow, and the critical shear stress are considered in a Monte Carlo evaluation of the uncertainty in the MSHA procedure applied to Piney Run Creek. It was found that for the 100-year flow the instream structures had a 34.2 percent chance of moving (i.e. maximum shear > critical shear). Further evaluation of the procedure found that the instream structures have 32.5 and 24.9 percent chances of moving for the 50- and 25-year flows, respectively. It also was found that failing to consider the uncertainty in the critical shear stress, as is common in most design procedures, could result in a 20 to 30 percent underestimation of the true failure probability of an instream structure. The results of the uncertainty analysis give engineers and decision makers a clearer picture of the safety and acceptability of the design.

Keywords: Uncertainty Analysis, Instream Structures, Stream Restoration, Critical Shear

1. INTRODUCTION

To meet the needs for flood and stormwater management and wastewater conveyance in urban areas streams have been substantially changed from their natural state both physically and biologically. Meandering streams have been straightened and pool and riffle sequences have been smoothed to uniform depths throughout the river. During dry weather periods groundwater flows have been reduced because of reductions in infiltration resulting from impervious land cover, and treated wastewater flows often replace the natural groundwater flow as the primary source of baseflow. Natural riparian vegetation often is cut to improve the hydraulic efficiency of the drainage, and the natural channel bed may be replaced with concrete. These and many other effects of urbanization have resulted in streams changing from attractive, biologically diverse ecosystems to unattractive, biologically limited drainage ditches. Also many streams that have been affected by changed runoff, straightening, and channelization in urban areas have resisted the imposed changes and have become unstable potentially damaging roads and other property near these streams. These streams need to be stabilized.

In recent years, many communities have tried to restore urban streams to a more natural condition and to stabilize unstable streams using ecologically friendly methods. Naturalization is not restoring a stream to its natural state, but rather restoring the stream so that it may provide more natural habitat while still meeting its flood and stormwater management and wastewater conveyance functions. A number of procedures have been developed for stream naturalization/restoration (e.g., FISRWG, 1998; Shields et al. 2003). However, considerable uncertainty exists in the application of these procedures particularly with respect to stream stability. For example, many stream restorations do not survive their first large storm and many others are made so strong that concrete is replaced with “green” concrete (rip-rap, concrete blocks, etc.) that looks better than concrete, but does not restore biological functions. Because of the large uncertainty in the evaluation of stream stability large safety factors often are applied in design, and/or very conservative assumptions are made in selecting the design criteria for stream stability.

In this paper, uncertainty analysis is applied to stream stability criteria developed by the Maryland (USA) State Highway Administration, MSHA (Flores, 2000, written commun.) to ensure that instream structures can survive potential high flows. Through an example, the conservative nature of the proposed procedure is shown and suggestions are made regarding improvements in the design procedure.

2. SAFETY AND STABILITY OF INSTREAM STRUCTURES

Various instream devices or structures have been applied in stream naturalization, including deflectors—used on alternate banks to produce a meandering thalweg or to stabilize a meandering stream; small weirs or sills—used to reestablish pool-riffle sequences; boulder placement and fish shelters; and methods for replacement of natural bed sediments (Johnson and Rinaldi, 1998). Instream structures reduce erosion risk by shifting high velocity gradients and boundary stresses away from the near bank area. Properly placed structures can also provide grade control, enhance fish habitat, create a more “natural” appearance, and are generally less expensive than more traditional stability methods, such as rip-rap (Rosgen, 2001).

The procedure developed by the MSHA to ensure the safety/stability of the designed instream structures involves doing a standard-step backwater analysis of the designed reach for the case of the 100-year flow using HEC-RAS (U.S. Army Corps of Engineers, 2002). The maximum shear stress for the 100-year flow also is computed with HEC-RAS and is compared to the critical shear stress needed to move the rocks used to construct the instream structures. If the maximum shear stress is less than the critical shear stress, the instream structures are considered stable and safe. The critical shear stress is obtained from Rosgen's (in Leopold et al., 1998) extenstion of the Shield's diagram fit to data obtained from Leopold et al. (1964) that compare critical shear stress and grain diameter. The relation of critical shear stress to grain diameter developed by Rosgen for shears greater than 0.479 N/m^2 (= 0.01 lb/ft^2) is shown in Fig. 1.

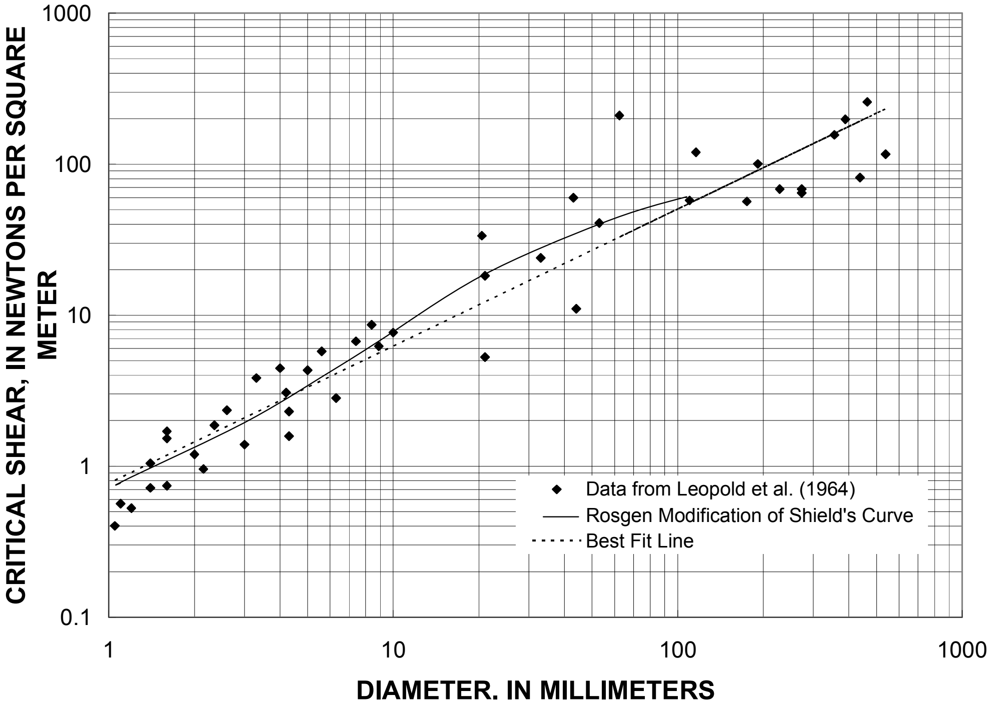

Fig. 1. Relation between particle diameter and critical shear stress on the basis of data from Leopold et al. (1964) as determined by linear regression of logarithms of the data (i.e. best fit line) and from Rosgen's modification of the Shield's curve from Leopold et al. (1998).

3. CASE STUDY

Piney Run Creek in Maryland, USA, was straightened in 1955 to accommodate the construction of Interstate Highway 83 (I-83). In the 40 years following its straightening Piney Run Creek migrated more than 12 m toward I-83. This migration threatened the stability of the highway and the MSHA took action to stabilize the stream and to restore it to more natural conditions. The objective of the naturalization was to replicate the stable characteristics of a more natural reference reach downstream from the project site. Instream structures such as rock vanes, cross vanes, and J-hooks were used to relieve stress from the banks and prevent the channel from migrating toward I-83. Other bank protection methods used for embankment slope stability and improving native vegetation also were applied.

The drainage area at the upstream end of the project site is 6.8 km^2 and for the downstream end of the project site is 8.1 km^2. The 198 m long study reach was divided into two sections with 100-year flows based on the drainage areas for the upstream (applied to the first 95 m) and downstream (applied to the last 103 m) ends of the system applied in HEC-RAS (U.S. Army Corps of Engineers, 2002). Using the U.S. Geological Survey regional regression equations for Maryland (Dillow, 1996) the 100-year flows for the upstream and downstream portions of the study reach were estimated as 59.4 and 65.9 m^3/s, respectively. Boulders with a diameter of 0.61 m (2 ft) were selected for the instream structures, and from an extension of Rosgen's curve in Figure 1 it was estimated that the critical shear for these boulders would be 383 N/m^2 (8 lb/ft^2). The HEC-RAS simulation of the design conditions indicated that the maximum shear would be 335 N/m^2, and, thus, the design was considered appropriate.

Shortly after the stream was restored, the constructed reach was substantially tested by a storm in December 2000 that resulted in approximately the 25-year runoff event. The site was monitored immediately after the storm and variations in cross section and profile geometry were recorded. A short section at the most upstream portion of the project, which was constructed with a bank height above bankfull stage, experienced bank erosion. The remainder of the constructed stream graded in accordance with the stable design geometry based on the bankfull discharge withstood the high magnitude flood and did not experience any change in cross section or profile (Flores, 2002, written commun.). This early test confirmed the safety of the design of the instream structures. The uncertainty evaluation presented in the following subsections provides insight on the overall safety of the design procedure.

3.1 UNCERTAINTIES AFFECTING THE DESIGN PROCEDURE

There are two primary types of uncertainty in the design procedure developed by the MSHA—uncertainty in the determination of the critical shear stress and uncertainty in the computed maximum shear. The uncertainty in the computed maximum shear is in turn primarily a function of the uncertainty in the estimated 100-year flow and the hydraulic roughness of the main channel, overbank areas, and instream structures. Uncertainty also is likely in the channel geometry. However, the U.S. Army Corps of Engineers (1986) and Oegema and McBean (1987) found that the effects of channel geometry uncertainties on the uncertainty in the computed water-surface profile are substantially smaller than those of Manning's n (one fourth or less) unless the geometry is crudely estimated (e.g., from topographic maps with 3-m contour intervals). Given the care put into the construction of restored streams, it is reasonable to assume that uncertainties in channel geometry will have a small effect on the computed maximum shear.

3.1.1 Uncertainty in Manning's n

The uncertainty in Manning's n has been investigated by a number of researchers. Manning's n normally is determined from experience using reference photographs (e.g., Barnes, 1967) and tables (e.g., Chow, 1959). The most extensive evaluation of this experience-based approach was done by the U.S. Army Corps of Engineers (1986). In this study, a group of 77 experienced engineers was asked to estimate the value of Manning's n for 10 stream reaches. Each participant was shown pictures of each stream reach. The stream reaches were highly varied including channels from the southwestern, midwestern, and eastern U.S. The standard deviation (SD) was found to be a function of n as follows

$$SD(n) = n[\exp((0.582 + 0.10 \ln n)^2) -1]^{1/2} \tag{1}$$

The U.S. Army Corps of Engineers also found the estimated values of Manning's n to follow a lognormal distribution. The standard deviation of the logarithms of n then can be determined from the properties of the lognormal distribution (Ang and Tang, 1975, p. 105) as

$$SD(\ln n) = 0.582 + 0.1 \ln n \tag{2}$$

In the Piney Run Creek example, three distinct values of Manning's n were used: 0.035 for the main channel without instream structures, 0.05 for the main channel with instream structures, and 0.08 for the overbank/floodplain areas. On the basis of eq. (2) the standard deviation of logarithms of n then was estimated to be 0.248, 0.282, and 0.329 for the main channel without structures, the main channel with structures, and the overbank areas, respectively. The respective n values were converted to equivalent mean of the lognormal variables, and the respective mean and standard deviation of the logarithms of n were generated in a Monte Carlo Simulation (MCS) analysis of the MSHA design procedure.

The U.S. Army Corps of Engineers (1986) study focused on the determination of Manning's n for existing streams using engineering judgment. It is conceivable that in a constructed stream a less uncertain estimate of Manning's n might be appropriate, thus, reducing some of the uncertainty in the design procedure. McBean et al. (1984) cited a study done by the Alberta Research Council, Transportation and Surface Water Department, on the Peace River indicating the coefficient of variation (CV) for measured n values to be between 12 and 18 percent. The higher of these values was chosen for an alternative MCS analysis of the MSHA design procedure. Only the CV of Manning's n changed while the distribution and mean remained the same in the alternative MCS analysis.

3.1.2 Uncertainty in the Estimated Flood Flows

It is normal in the determination and reporting of the regional regression equations by the U.S. Geological Survey to include the average standard error of prediction in percent for the equations. Piney Run Creek is in the Piedmont Province of Maryland, and, thus, the average standard error is 43, 40, and 37 percent for the 100-, 50-, and 25-year flows, respectively (Dillow, 1996). The errors in the regression equations were assumed to be lognormally distributed since the equations were developed by multiple linear regression in logarithmic space. The average standard deviations in percent were assumed to be equal to the CVs, although this assumption is most correct for lognormal distributions with CVs ≤ 0.3 (Ang and Tang, 1975, p. 105).

3.1.3 Uncertainty in the Critical Shear Stress

To facilitate the uncertainty analysis a relation between critical shear stress and particle diameter was derived for the data provided by Leopold et al. (1964) with critical shear stresses greater than 0.479 N/m^2 (0.01 lb/ft^2) as shown in Fig. 1. This relation is expressed as follows

$$\tau_C = 0.7709\ D^{0.9078} \tag{3}$$

where τ_C is the critical shear in N/m^2 and D is the particle diameter in mm. The hypothesis that the residuals of eq. (3) are normally distributed could not be rejected by the chi-square test or the skewness test of normality at the 0.02 percent significance level. The standard deviation of the logarithms of the residuals was found to be 0.554. Thus, for a boulder with a diameter of 0.61 m (2 ft) the estimated critical shear is 260.3 N/m^2. The logarithm of this value was taken as the mean of the logarithms and was combined with the standard deviation of the logarithms of the residuals to characterize the lognormal distribution of the critical shear.

Grass (1970) did an evaluation of the uncertainty in the original Shields diagram of the critical shear stress. He found that a CV of 0.3 was appropriate. Lopez and Garcia (1997) later used this value in their evaluation of the uncertainty in the initiation of sediment movement. Thus, this value was chosen for an alternative MCS analysis of the MSHA design procedure. Only the CV of the critical shear changed while the distribution and mean remained the same in the alternative MCS analysis.

3.2 MONTE CARLO PROCEDURE AND TEST CASES

Monte Carlo Simulation (MCS) was used to evaluate the uncertainty in the MSHA design procedure. A computer program was developed to do the following steps.

1) Generate random values of the 100-year flow corresponding to a lognormal distribution with a mean of the logarithms equal to the logarithm of the expected upstream and downstream flows and a coefficient of variation of 0.43. Both the upstream and downstream flows had identical standardized deviations from the logarithmic mean to avoid the unrealistic result of flow decreasing from upstream to downstream in the MCS.
2) Generate random values of Manning’s n corresponding to a lognormal distribution with the mean and standard deviation as previously described. For the main channel without instream structures, main channel with instream structures, and the overbank areas identical standard normal variables were used with the appropriate SD(ln n) as per eq. (2) to compute the deviations from the logarithmic mean to avoid unrealistic results such as overbank areas having smaller flow resistance than the main channel in the MCS.
3) Write the input file for the HEC-2 Water Surface Profiles (U.S. Army Corps of Engineers, 1990) for the study reach inserting the randomly generated flow and Manning’s n values.
4) Call HEC-2 as a subroutine to compute the maximum shear for the study reach corresponding to the randomly generated flow and Manning’s n values. HEC-2 (the

predecessor of HEC-RAS) was selected for this analysis because it is easier to set up as a subroutine in the MCS program.

5) Generate random values of the critical shear corresponding to a lognormal distribution with the mean and standard deviation as previously described.
6) Compare the computed maximum shear to the randomly generated critical shear. If maximum shear is greater than critical shear, the design is considered to have failed.

One thousand simulations were done and the probability of failure is computed as the total number of failures divided by 1,000. The statistics of various design parameters also were computed and histograms of key outputs prepared to check that the MCS was done correctly. Figure 2 compares the histograms of the computed maximum shear and the generated critical shear. The overlap of these histograms reflects the probability of failure.

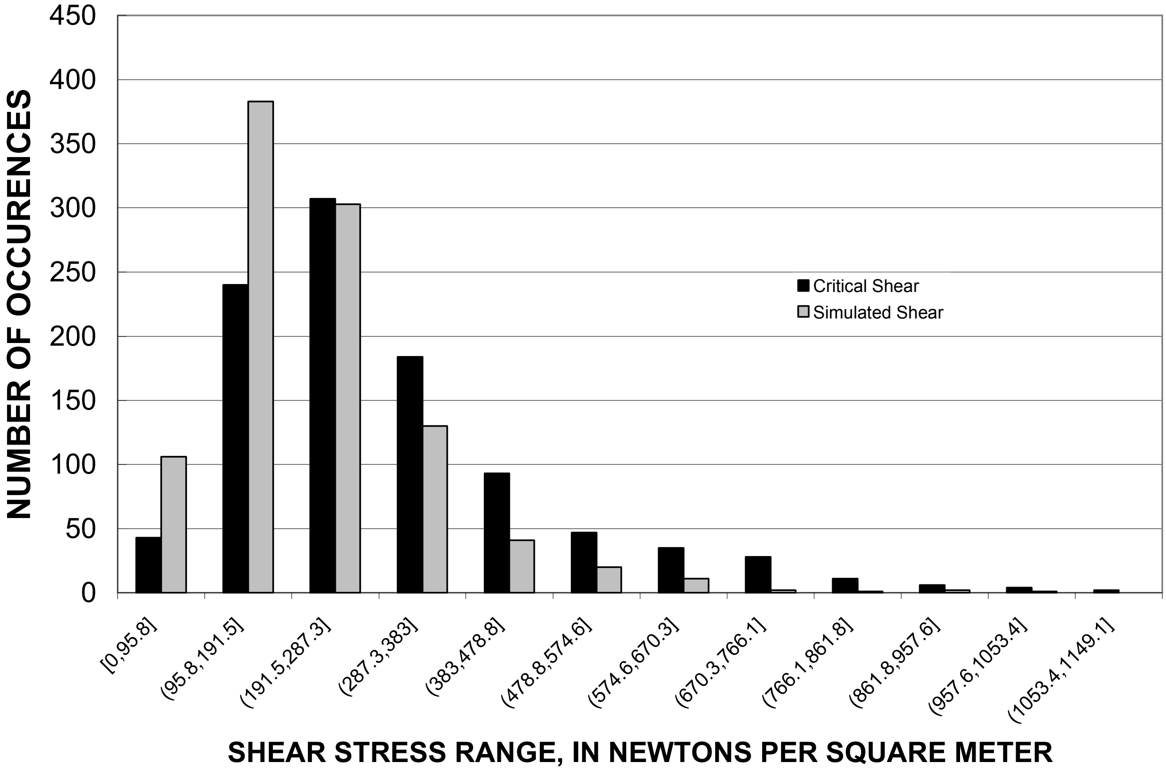

Fig. 2. Comparison of distributions of simulated maximum and critical shear stresses for the 100-year flow for Piney Run Creek, Maryland, USA for scenario 1.

In addition to considering the reliability of the MSHA design procedure it was decided to consider variations of this procedure wherein the target flow is the 25- or 50-year flow. The upstream and downstream flows for the 25-year return period are 36.2 and 40.3 m^3/s, respectively, and the upstream and downstream flows for the 50-year return period are 46.9 and 52.1 m^3/s, respectively. Five sets of MCS runs (i.e. scenarios) were made for each of the target flow levels utilizing different assumptions regarding the uncertainty in Manning's n and the critical shear as follows.

1) Manning's n uncertainty from U.S. Army Corps of Engineers (1986) and critical shear uncertainty with a standard error of the logarithms of 0.554.

2) Manning's n uncertainty from U.S. Army Corps of Engineers (1986) and critical shear uncertainty with a standard error of the logarithms of 0.30.
3) Manning's n uncertainty from U.S. Army Corps of Engineers (1986) and critical shear fixed at the design value of 383 N/m^2 (8 lb/ft^2).
4) Manning's n uncertainty from U.S. Army Corps of Engineers (1986) and critical shear fixed at the value from eq. (3) for a 610 mm diameter boulder (260.3 N/m^2).
5) Manning's n uncertainty from McBean et al. (1984) and critical shear uncertainty with a standard error of the logarithms of 0.554.

4. RESULTS

The probability that the maximum computed shear would exceed the critical shear is listed in Table 1 for each of the 5 previously listed scenarios for the three flow levels of 25-, 50-, and 100-year return periods. For statistically independent events the probability of failure may be estimated from the concept of conditional probability as follows

$$P(F) = P(F \mid E)P(E) \tag{4}$$

where P(F) is the probability of failure (i.e. maximum shear > critical shear), $P(F \mid E)$ is the probability of failure given that event E (flow of given return period) occurs, and P(E) the probability of event E (i.e. one divided by the return period). The results listed in Table 1 do not conform with eq. (4). This is because the maximum shear is only weakly related to the flow rate. Because the flow is spread across the flood plain the hydraulic radius only increases slightly as the flow increases from the 25-year to the 50- and 100-year flows. Also, the maximum energy slope is more dependent on the slope of the constructed pool and riffle sequence than on the flow rate.

Table 1. Probability that the computed maximum shear will exceed the critical shear for the 0.61 m boulders used in the instream structures for the restored section of Piney Run Creek, Maryland, USA.

Return Period (yrs)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
100	0.342	0.305	0.072	0.273	0.326
50	0.325	0.258	0.061	0.231	0.293
25	0.285	0.219	0.043	0.170	0.261

Comparing Scenarios 1, 2, and 4, the effect of uncertainty in the determination of the critical shear can be evaluated. If the uncertainty in the critical shear is ignored as is common in most design procedures (Scenario 4), the failure probability is underestimated by 20.1, 28.9, and 40.3 percent relative to the 100-, 50-, and 25-year flow cases considering the full uncertainty in the best fit line (eq. (3)) (Scenario 1). Similarly, the failure probability is underestimated by Scenario 4 by 10.5, 10.5, and 22.4 percent relative to the 100-, 50-, and 25-year flow cases considering the uncertainty in critical shear as per the analysis of Grass (1970) (Scenario 2).

Comparing Scenarios 1 and 2 and Scenarios 1 and 5, it can be seen that the uncertainty in the critical shear and the uncertainty in Manning's n have a similar effect on the uncertainty in the computed failure probability. A 45 percent reduction in the critical shear uncertainty results in 10.8, 20.6, and 12.0 percent reductions (Scenarios 1 and 2) in the failure probability for the 100-, 50-, and 25-year flows, respectively. Whereas 27, 36, and 45 percent reductions in the uncertainty in Manning's n for the main channel without structures, main channel with structures, and overbank areas, respectively, resulted in 4.7 and 9.8 percent reductions (Scenarios 1 and 5) in the failure probability for the 100- and 50-year flows. The failure probability for the 25-year flow increased for a decrease in uncertainty in Manning's n. This may be an indication that 1,000 simulations may not be sufficient to accurately estimate the failure probability.

Finally, the original design estimated that the critical shear stress for the 610 mm boulders was 383 N/m^2, however, the best fit logarithmic relation estimated that the critical shear stress for the 610 mm boulders was 260.3 N/m^2. Use of the original design critical shear value results in about a 74 percent underestimation of the true failure probability of the instream structures (Scenario 4 versus Scenario 3).

5. CONCLUSIONS

An uncertainty analysis of a procedure for the design of instream structures used in stream restoration/naturalization to resist high flow conditions used by the Maryland State Highway Administration (MSHA) was done. In this procedure the maximum shear stress in the designed channel computed for the 100-year flow is compared to the critical shear stress of the boulders used to build the structure. If the maximum shear stress is less than the critical shear stress, the structure is considered safe. Uncertainty in Manning's n, the design flow, and the critical shear stress were considered in a Monte Carlo evaluation of the MSHA procedure applied to Piney Run Creek.

It was found that for the 100-year flow the instream structures had a 34.2 percent chance of moving. At first glance, this appears to be a positive result. However, further evaluation of the procedure found that the instream structures have 32.5 and 24.9 percent chances of moving for the 50- and 25-year flows, respectively. The weak dependence of the maximum shear stress on the flow rate leads to the conclusion that the MSHA procedure may lead to a false sense of security. On the other hand, a one in three chance of failure for the 50-year flow or a one in four chance of failure for the 25-year flow might be acceptable risks. Uncertainty analysis gives engineers and decision makers a clearer picture of the safety of the design and provides better information to determine the acceptability of the design.

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