Fault Tree Analysis of Bridge Failure due to Scour and Channel Instability

By Peggy A. Johnson[1]

Abstract: Fault tree analysis is a systematic method of analyzing events that lead to an undesirable event. Fault trees can be used to assess the probability of failure of a system (or top event), to compare design alternatives, to identify critical events that will significantly contribute to the occurrence of the top event, and to determine the sensitivity of the probability of failure of the top event to various contributions of basic events. In this paper, fault tree analysis is used to determine the probability of failure of a bridge due to scour and other geomorphic channel instabilities. This analysis permits an examination of a very complex system of interactions and processes that are not well understood. Minimal knowledge regarding the actual processes of scour and channel instability is required for a fault tree analysis. Three examples of analyses for actual bridges are provided showing different combinations of scour (local and contraction) and geomorphic instabilities (channel widening and degradation) at both the abutments and piers. Riprap placed at the abutments for protection is also included in the analyses.

INTRODUCTION

Scour at bridges is a very complex process. Scour and channel instability processes, including local scour at the piers and abutments, contraction scour, channel bed degradation, channel widening, and lateral migration, can occur simultaneously. The sum and interaction of all of these river processes create a very complex phenomenon that has, so far, eluded mathematical modeling. To further complicate a mathematical solution, mitigation measures, such as riprap, grout bags, and gabions, may be in place at the abutments and piers. Any mathematical model would have to account for these structures as well.

The interactions of the processes of local scour, contraction scour, channel bed degradation, channel widening, and lateral migration are unknown. Federal Highway Administration guidelines (Richardson and Davis 1995) recommend that local and contraction scour and bed degradation be assumed to be independent. Based on this assumption, the total vertical erosion at the bridge is then simply the sum of the scour and bed degradation. Because no other formation is available, this assumption provides a conservative estimate. Lateral channel instabilities are typically considered separately from scour and bed degradation, and the estimate of their effect on bridge foundations is often based on judgment and experience. The interactions of scour and channel instabilities are very difficult to predict. Certainly the processes may not be independent but rather related to each other and the resulting impact on the bridge.

One way to examine the possible interactions of all of these processes and their effect on bridge piers and abutments is to use fault tree analysis. Fault tree analysis is a systematic method of analyzing fault sequences that lead to an undesirable event, such as a bridge failure. A fault tree analysis can be qualitative, which provides information on the most important events or sequence of events in the tree, or it can be quantitative, which provides an estimate of the probability of occurrence of an undesirable event. In this paper, fault tree analysis is used to examine the interactions and sequences of events that could lead to a bridge failure due to scour or channel instabilities at the piers or abutments. Based on the fault tree analysis, the probability of failure of the bridge due to various combinations of scour and channel instabilities will be calculated.

BRIDGE SCOUR AND GEOMORPHIC CHANNEL INSTABILITY

Bridge scour is the erosion of stream channel bed material in the vicinity of abutments or piers. It is categorized as (1) local scour that occurs at the abutments or piers and is caused by the obstruction to flow; (2) contraction scour that occurs under and near the bridge opening and generally lowers the channel bed due to flow constriction; and (3) channel degradation that is a lowering of the entire channel bed and that would occur regardless of whether the bridge is in place or not. Guidance on predicting scour is given in HEC-18 (Richardson and Davis 1995), although many other prediction methods exist in the literature. Scour and degradation are typically thought to be independent so that the total scour at a bridge is simply the sum of the three. The prediction equations for local pier and abutment scour were developed as conservative equations (i.e., the equations enveloped all of the calibration data rather than being best-fit curves) and, thus, tend to yield high estimates of scour (Jones 1983; Johnson 1995; Landers and Mueller 1996). There is considerable uncertainty in the local scour equations. The pier scour equation given in HEC-18 is

$$y_s = 2.0K_1K_2K_3K_4y\left(\frac{b}{y}\right)^{0.65}\mathsf{F}^{0.43} \tag{1}$$

where y_s = pier scour; K_{1-4} = correction factors for shape, alignment to flow, bed forms, and sediment gradation, respectively; b = pier width; y = flow depth; and F = Froude number. In most cases, the predominant sources of uncertainty in (1) are model uncertainty and uncertainty in estimating the K parameters. Model uncertainty results from using a model or equation that may not be completely representative of the physical processes. In the case of pier scour, the model has been developed from small scale laboratory experimental results that are then extrapolated to the prototype scale. A model form was assumed (in the case of pier scour, the power form was assumed) and the equation calibrated using the laboratory data. Complexities in the field cannot be modeled entirely in the laboratory, and the appropriateness of small scale models to predict phenomena at prototype structures is unknown. Model uncertainty can be incorporated into an equation using a model correction or bias factor (Ang and Tang 1984). Pa-

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rameter uncertainty results from an inability to accurately assess parameters and model coefficients required in the model. The tables and figures from which the K factors are determined are rather vague, and the engineer must determine the value based on judgment.

Several abutment scour equations exist in HEC-18 and elsewhere. The inability to model the scour either mathematically or physically results in considerable uncertainty in all of these equations whether they are developed from field data or laboratory data. Abutment scour equations typically yield very large values of scour. As an example of a very simple abutment scour equation, HEC-18 gives

$$y_s = 4yK_{a2}\mathsf{F}^{0.33}\left(\frac{K_{a1}}{0.55}\right) \tag{2}$$

where K_{a1} = abutment shape coefficient; and K_{a2} = abutment skew coefficient. K_{a1} and K_{a2} are determined from tables provided in HEC-18 based on the shape (vertical-wall or spill-through) and angle of the bridge abutments to the main channel. Uncertainty in (2) is primarily due to model uncertainty. Additional information on uncertainty in local scour equations and parameters can be found in Johnson (1992, 1996a) and Johnson and Dock (1998).

Live bed contraction scour, which occurs when the sediment on the channel bed is in motion, can be computed from the modified Laursen equation as (Richardson and Davis 1995)

$$y_s = y_1\left(\frac{Q_2}{Q_1}\right)^{6/7}\left(\frac{W_1}{W_2}\right)^{k_1} - y_1 \tag{3}$$

where y = average depth in the main channel; Q = flow rate; W = bottom width of the channel; k_1 = exponent based on the bed material and the bed material transport; subscript 1 = upstream channel; subscript 2 = contracted section; and y_0 = existing depth in the contracted section before scour.

Prediction of channel degradation requires the use of a mathematical model or years of data showing trends in channel bed changes. Most alluvial channels experience long-term degradation; however, the engineer is concerned only with that which occurs over the life of the bridge. The long-term degradation process can be accelerated considerably by human activities, such as channel straightening and urbanization. This often causes the channel to become unstable and incise. In this case it is sometimes possible to predict the near term bed degradation using a regression equation based on bed elevation data collected at the site.

In addition to the scour processes listed previously, bridge foundations can also be affected by channel widening and lateral migration. Channel widening has been even more difficult to predict than channel degradation. Several mathematical models exist to predict channel widening, although they have not been well tested in the field (Darby and Thorne 1996; ASCE 1998). Similar to channel degradation, channel widening can sometimes be predicted for a specific site based on widening rates collected in the field. Lateral migration can be predicted in a similar way. Data can also be taken from aerial photographs and sequential topographic maps. Both widening and lateral migration can affect the bridge foundations in the floodplain or overbank area as the channel widens or encroaches on piers with shallower foundations or abutments set back into the floodplain.

FAULT TREE ANALYSIS

A fault tree diagram is a systematic method of identifying faults and their interactions in a complex system. A fault tree can assist in the identification of paths to failure and can be used to single out critical events. Fault trees also can be used to assess the probability of failure for the system (or top event), to compare design alternatives, to identify critical events that will significantly contribute to the occurrence of the top event, and to determine the sensitivity of the probability of failure of the top event to various contributions of basic events.

Fig. 1 shows a simple fault tree that is composed of four types of events. The top event T is an undesired event, such as the failure of a system. Basic events (E_3 and E_6 in Fig. 1), sometimes referred to as terminal events, cannot be decomposed further into other events. Secondary events (E_5 in Fig. 1), sometimes referred to as basic events, are those that are external to the system that are purposely not decomposed further. Event E_4 is called a switch event. The occurrence of a switch event changes the operating condition of the system (Ang and Tang 1984). The events can be combined in a number of ways, most commonly through intersections or unions, shown in Fig. 1. Fault tree diagramming is explained in greater

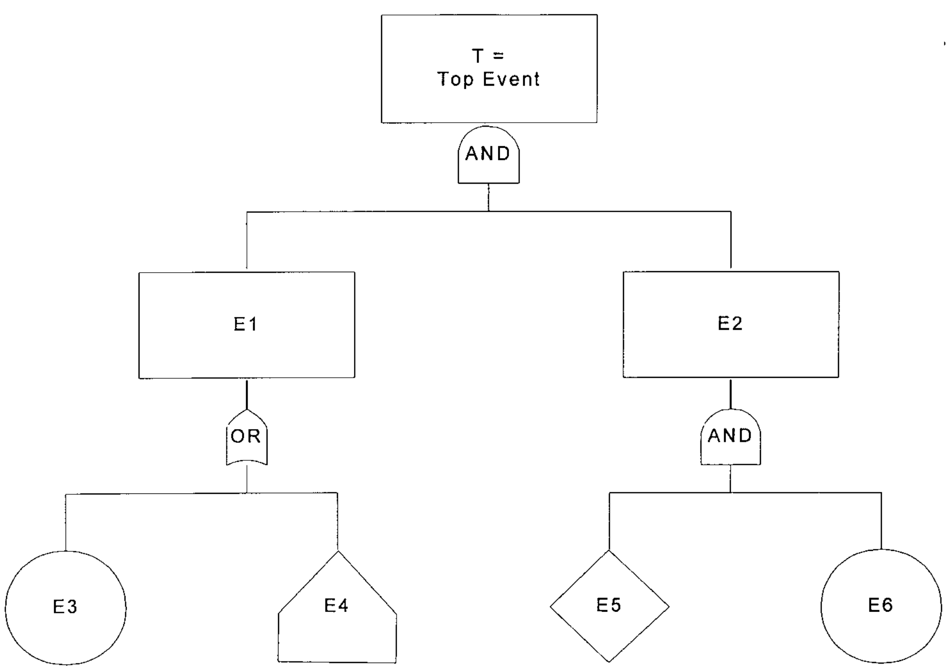

FIG. 1. Simple Fault Tree

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detail in Ang and Tang (1984), Lee et al. (1985), and Ayyub and McCuen (1997).

There are several limitations to fault tree analysis (Sundararajan 1991). For very complex systems that require large fault trees, it is possible to overlook or miss failure modes. In this case, the probability of occurrence of the top event or other events could be nonconservative. Another possible shortcoming of fault tree analysis is that there are only two possibilities of the occurrence of any event—the event either occurs or it does not. Fuzzy or changing failure modes cannot be readily accounted for.

Fault tree analysis can be either qualitative or quantitative, depending on the desired output. Qualitative analyses provide information about the importance of the basic events. Cut sets are commonly used for this type of analysis. A cut set is a combination of terminal events that is sufficient to cause an occurrence of the top event (Sundararajan 1991; Ayyub and McCuen 1997). In other words, if all terminal events in a cut set occur, then the top event will occur. A minimal cut set is defined as the smallest subset that is sufficient and necessary to cause the occurrence of the top event.

In a quantitative fault tree analysis, the top event is related to subevents and basic faults through AND/OR gates. An AND gate is shown in Fig. 1 and represents the intersection of two or more events. For example, for the simple fault tree shown in Fig. 1

$$p(T) = p(E_1 \cap E_2) = p(E_1)p(E_2|E_1) \quad (4)$$

If E_1 and E_2 are independent events, then (4) reduces to

$$p(T) = p(E_1)p(E_2) \quad (5)$$

An OR gate, shown in Fig. 1, represents the union of two or more events. Based on Fig. 1

$$p(T) = p(E_1 \cup E_2) = p(E_1) + p(E_2) - p(E_1 \cap E_2) \quad (6)$$

If E_1 and E_2 are dependent events, then

$$p(T) = p(E_1) + p(E_2) - p(E_1)p(E_2|E_1) \quad (7)$$

If E_1 and E_2 are independent events, then

$$p(T) = p(E_1) + p(E_2) - p(E_1)p(E_2) \quad (8)$$

If the term $p(E_1 \cap E_2)$ in (4) and (6) is small, then that term can often be neglected without a significant change in the result. This will provide a conservative estimate of $p(T)$.

If all events in a fault tree are independent, then the calculations are straightforward. However, if some of the events are dependent, then information regarding the conditional probabilities is required. For example, in (4) and (7), $p(E_2|E_1)$ must be known. It is often the case that such information is lacking. In this case, the analyst can determine a range of probabilities for the top event based on upper and lower limits of the basic events. As an example, if $p(E_2|E_1)$ in (4) is unknown, then the boundaries of this term are (Ang and Tang 1984; Ayyub and McCuen 1997)

$$p(E_1)p(E_2) \le p(E_2|E_1) \le \min[p(E_1), p(E_2)] \quad (9)$$

which represents the range from completely independent to perfectly correlated, respectively. Thus, the range of $p(T)$ in (7) can be represented by

$$p(E_1) + p(E_2) - \min[p(E_1), p(E_2)] \le p(T) \le p(E_1) + p(E_2) - p(E_1)p(E_2) \quad (10)$$

FAULT TREE ANALYSIS OF BRIDGE SCOUR AND CHANNEL INSTABILITY

Scour at bridges can be attributed to channel degradation, contraction scour, and local (abutment and pier) scour. In addition, bridge foundations can be adversely affected by geomorphic instabilities, such as widening and lateral migration. Fig. 2 shows the top portion of the fault tree diagram for this situation, where the top event is failure of the bridge due to scour and channel instabilities. In this study, failure is defined as the point at which the scour depth reaches the bottom of the pier footing whether or not piles are in place beneath the footing. In some cases, bridges are designed to be stable with exposed piles. In the definition of failure used here, it is assumed that this is not the case. A bridge can fail due to failure at the abutment or at the piers or both. Therefore, the events

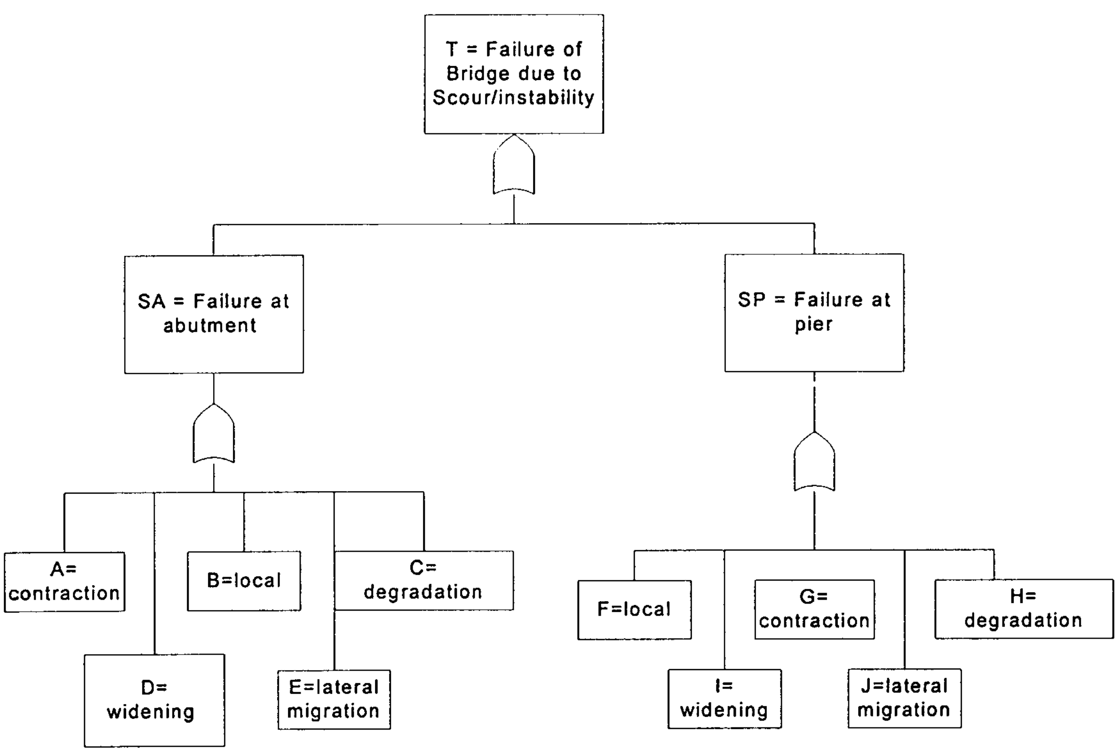

FIG. 2. Main Fault Tree Diagram for Scour and Channel Instability at Bridges

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of failure at the abutments and piers (S_A and S_P, respectively) are connected by an OR gate. Abutment failure can occur due to any of the following: channel widening, lateral migration of the channel, local scour, contraction scour, or channel degradation. Likewise, pier failure can result from any combination of these events. Therefore, these five events are connected by an OR gate for each abutment and pier failure.

Each of events A–J can be decomposed further. Fig. 3 shows the portion of the fault tree for local scour at the abutments. Riprap is often placed at abutments to protect them from local scour. If the riprap is moved by a large hydrologic event, then the abutment is exposed to scour. It follows that a bridge abutment can fail due to local scour if both the riprap fails (B_2) and excessive scour occurs (B_1). Therefore, events B_1 and B_2 are connected by an AND gate. For the riprap to fail, an event in excess of the critical shear stress of the riprap must occur. Fig. 3 shows that events B_5 (an excessive shear stress) and B_6 (the critical shear stress of the riprap is inadequate) are connected by an AND gate so that both of these events have to occur for the riprap to fail. Abutment scour in excess of the foundation depth occurs if both an excessive hydrologic event occurs causing scour at the abutment (event B_3) and the foundation depth is inadequately shallow (event B_4); therefore, events B_3 and B_4 are connected by an AND gate. Similar decompositions can be developed for the remaining events A–J. For erosion at the piers in this study, riprap was not considered. It was assumed that either the riprap is not in place or that it is ineffective in protecting the pier.

The probability of occurrence of each of the basic events in the fault tree are required to determine the probability of the top event. This is not a simple task. However, simulation of scour equations, such as those presented in HEC-18 (Richardson and Davis 1995), and other geomorphic relationships, can be used to estimate these probabilities. Simulation requires a coefficient of variation and probability distribution for each of the variables in the equations. Although this information is known or can be estimated for certain variables (Johnson 1996a; Gates and Al-Zahrani 1996), it is not always known. However, a lower limit, an upper limit, and the most likely value of a variable can often be established based on engineering judgment and physical limitations. In this case a distribution, such as a symmetrical or asymmetrical triangular, can be assumed and the coefficient of variation computed accordingly (Ang and Tang 1984). In the next section, three examples are provided to demonstrate the calculation of $p(T)$. In each of the examples, the use of simulation to calculate the probabilities of the basic events will be discussed.

EXAMPLES

Route 66 Bridge over Piney Creek, Clarion County, Pa.

The Route 66 bridge over Piney Creek is located near Limestone in Clarion County in the Appalachian Plateau physiographic region of Pennsylvania. This bridge failed in July 1996, during an ~50-year storm. This same storm caused multiple bridge failures in western Pennsylvania. The failure was apparently caused by local and contraction scour around the abutments; there were no piers on this bridge. The vertical wall abutments are located at the edge of the channel banks with no setback from the stream. There was no riprap in place at the time of failure. Inspection following the failure showed that the stream channel upstream and downstream of the bridge was relatively stable and that widening, degradation, and lateral movement were not likely to be contributing factors in the failure.

Based on the physical setting and Fig. 2, only events A and B were considered. The probabilities of these events were determined from simulation of the basic events for local scour and contraction scour using the equations recommended in HEC-18 [(2) and (3), respectively] and by making the assumption that the abutment footing was located at 1.5 m below the channel bottom. For example, to determine $p(B)$, event B_3 (Fig. 3) was simulated by making assumptions regarding the coefficients of variation and the distributions. Table 1 provides the means, coefficients of variation, and the assumed distributions for each variable involved in the basic events. With the exception of λ, the means were taken from data and observations collected at the site. The value of λ was taken from Johnson (1995). Coefficients of variation and assumed distributions were based on previous studies [e.g., see Johnson (1992, 1995, 1996a), Johnson and Ayyub (1992), and Johnson

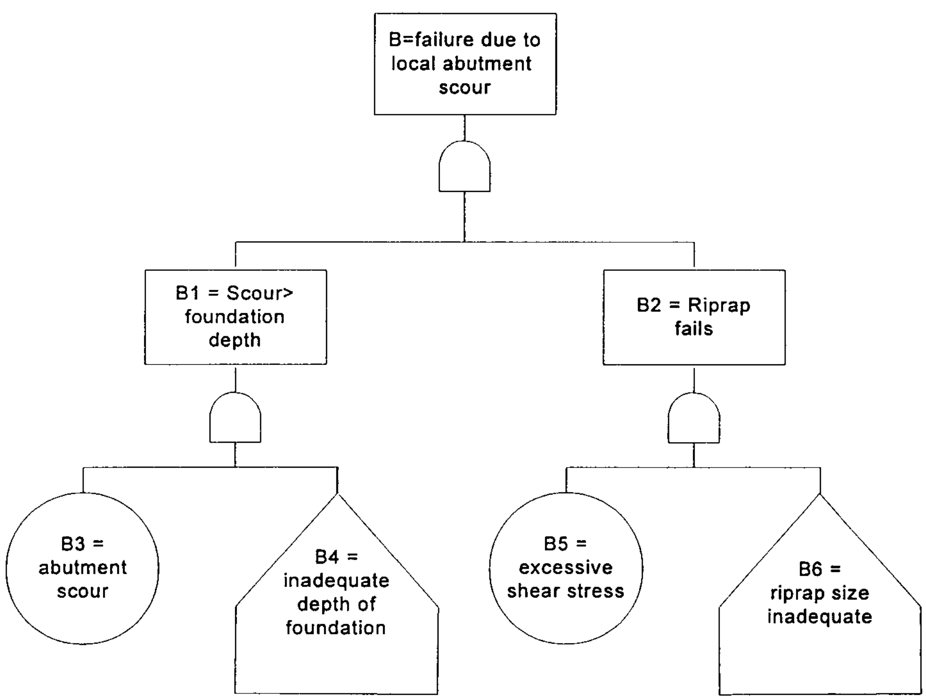

FIG. 3. Fault Tree Diagram Portion for Local Scour at Abutments (Continued from Fig. 2)

and Dock (1998)]. The probability of event B is then equal to $p(B_1) = p(B_3 \cap B_4)$.

From Fig. 2, the probability of failure of the bridge is given by

$$p(T) = p(S_A) = p(A \cup B) = p(A) + p(B) - p(A \cap B) \quad (11)$$

Assuming that events A and B are independent, (12) can then be written as

$$p(T) = p(A) + p(B) - p(A)p(B) \quad (12)$$

For the 50-year flood, and a 1.5-m-deep abutment foundation, $p(B) = 0.993$ and $p(A) = 0.517$. From (13), $p(T) = 0.997$. This is an extremely high probability of failure.

A second simulation was conducted to show how protection of the abutments using 30-cm riprap would have reduced the probability of failure of the abutments. In this case, probabilities of events A_1, A_2, B_1, and B_2 were required; therefore, B_3, B_5, A_3, and A_5 were simulated as follows. Failure is defined as the event that $\tau_a > \tau_c$, where τ_a = shear stress on the bed at the abutment and τ_c = critical shear stress = $\theta_c(\gamma_s - \gamma)D_{50}$, where γ = specific weight of water, γ_s = specific weight of sediment, D_{50} = median sediment size, and θ_c = Shield's parameter. Based on laboratory evidence (Melville and Raudkivi 1977; Johnson and Jones 1992), it was assumed that τ_a is $\sim 2.5\tau_0$, where τ_0 = average bottom shear stress = γyS and S = slope. Table 2 provides the means, coefficients of variation, and distributions assumed for this example. The coefficients of variation and distributions were based on prior work (Johnson 1996a,b). Referring to Fig. 3 and assuming independent events, the probability of abutment failure due to local scour can be calculated as

$$p(B) = p(B_1 \cap B_2) = p[(B_3 \cap B_4) \cap (B_5 \cap B_6)]$$

$$= p(B_3)p(B_4)p(B_5)p(B_6) \quad (13)$$

Similarly, the probability of abutment failure due to contraction scour becomes

$$p(A) = p(A_1 \cap A_2) = p(A_3)p(A_4)p(A_5)p(A_6) \quad (14)$$

TABLE 1. Means, Coefficients of Variation, and Distributions for Clarion County Example

Variable[a] (1)	Mean (2)	Coefficient of variation (3)	Distribution (4)
Flow velocity (m/s)	2.44	0.2	Symmetrical triangular
Flow depth (m)	2.43	0.2	Symmetrical triangular
K_{a1}	0.82	0.1	Uniform
K_{a2}	1.0	0.1	Uniform
λ_{La}	0.6	0.2	Normal
Q_t/Q_c	1.8	0.2	Normal
λ_C	1.0	0.2	Normal
Abutment depth (m)	1.5	0.01	Normal

[a] K_{a1} and K_{a2} = abutment scour correction factors for abutment shape and skew, respectively; λ_{La} = model correction factor for local abutment scour equation; Q_t/Q_c = flow contraction ratio; λ_C = model correction factor for contraction scour equation.

TABLE 2. Means, Coefficients of Variation, and Distributions For Clarion County Example Using Riprap

Variable (1)	Mean (2)	Coefficient of variation (3)	Distribution (4)
S	0.0045	0.25	Lognormal
γ (N/m^3)	9,810	0.023	Symmetrical triangular
θ_c	0.045	0.25	Normal

For the case of riprap protection, $p(A) = 0.0010$ and $p(B) = 0.0020$; therefore, from (8), the $p(S_A) = p(T) = 0.0030$. Using 30-cm riprap to protect the abutments decreased the probability of failure by two orders of magnitude. Additional contraction of the flow through the bridge opening due to the riprap was not considered but could potentially increase the contraction scour, thus slightly increasing $p(T)$.

Example from HEC-18

The second example is modified from an example given in HEC-18 (Richardson and Davis 1995) with some added assumptions where information was incomplete. In this example, the bridge has spill-through abutments with the right abutment set at the channel bank and the left abutment set back in the floodplain. There are six round-nosed piers. Additional details can be found in HEC-18. In this example, local scour at the piers and abutments as well as contraction scour were considered. The channel was assumed to be stable, so that degradation, widening, and lateral migration were not taken into account.

Simulations were conducted, again based on the HEC-18 abutment, pier, and contraction scour equations [(1)–(3)]. Table 3 provides the means, coefficients of variation, and assumed distributions, similar to the previous example. Although not stated in the data set, it was assumed that 23-cm riprap was protecting the abutments. Based on this assumption and Figs. 2 and 3, $p(B_1) = 0.520$, $p(B_2) = 2.78 \times 10^{-4}$, $p(A_1) = 0.657$; therefore, from (5), $p(A) = 0.000327$ and $p(B) = 0.000145$. In addition, $p(F) = 6.61 \times 10^{-4}$, $p(G) = 2.65 \times 10^{-4}$, and $p(S_P) = 0.00093$. The assumption is made that there is some correlation between scour at the pier and the abutment since contraction scour is occurring over the entire bed or some portion of the bed. This unknown relationship is reflected in a range of $p(T)$. The probability of bridge failure due to either abutment or pier scour or both can now be calculated from (6) and (9), resulting in $0.000925 \le p(T) \le 0.00125$.

TABLE 3. Means, Coefficients of Variation, and Distributions for HEC-18 Example

Variable[a] (1)	Mean (2)	Coefficient of variation (3)	Distribution (4)
Flow velocity at pier (m/s)	2.44	0.2	Symmetrical triangular
Flow velocity at abutment (m/s)	1.29	0.2	Symmetrical triangular
Flow depth at pier (m)	2.43	0.2	Symmetrical triangular
Flow depth at abutment (m)	0.83	0.2	Symmetrical triangular
Pier width (m)	1.52	0.001	Asymmetrical triangular
λ_{Lp}	1.0	0.2	Asymmetrical triangular
K_1	1.0	0	Uniform
K_2	1.0	0	Uniform
K_3	1.1	0.1	Uniform
K_4	1.0	0	Symmetrical triangular
K_{a1}	0.55	0.1	Uniform
K_{a2}	1.0	0.1	Uniform
λ_{La}	0.6	0.2	Normal
Q_t/Q_c	1.86	0.2	Normal
λ_C	1.0	0.2	Normal
Abutment depth (m)	1.5	0.01	Normal
Pier depth (m)	6.0	0.01	Normal

[a] λ_{Lp} = model correction factor for local pier scour equation; λ_{La} = model correction factor for local abutment scour; K_1, K_2, K_3, K_4 = pier scour correction factors for nose shape, angle of attack of flow, bed condition, and armoring, respectively.

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TABLE 4. Means, Coefficients of Variation, and Distributions for South Fork Forked Deer River Example

Variable (1)	Mean (2)	Coefficient of variation (3)	Distribution (4)
Flow velocity (m/s)	1.20	0.2	Symmetrical triangular
Flow depth (m)	5.0	0.2	Symmetrical triangular
Pier width (m)	2.1	0.001	Asymmetrical triangular
λ_{Lp}	1.0	0.2	Asymmetrical triangular
K_1	1.1	0.1	Uniform
K_2	1.0	0	Uniform
K_3	1.0	0	Uniform
K_4	1.0	0	Symmetrical triangular
Q_t/Q_c	1.1	0.2	Normal
λ_C	1.0	0.2	Normal
Degradation exponent	−0.013	0.002	Normal
λ_E	1.0	0.25	Normal
Pier depth (m)	3.9	0.01	Normal

Route 51 Bridge over the South Fork Forked Deer River, Tenn.

The final example is based on the Route 51 bridge over the South Fork Forked Deer River in west Tennessee. This bridge failed in 1973 due to local scour at the piers and rapid channel degradation and widening following channel straightening. Abutments were set well back into the floodplain and were unaffected by scour. Contraction scour was due only to piers in the floodplain and channel. From Fig. 2, events F–H were considered. Degradation (event H) occurring over a 5-year period was based on a previous study (Johnson and Simon 1997) as

$$\Delta y_E = 78.2(1 - \lambda_E t^{-0.013}) \tag{15}$$

where Δy_E = change in bed elevation due to degradation (m); λ_E = model correction factor; and t = years since channel straightening.

Table 4 provides the input data to the simulation for determining events F–H. Riprap at the piers was not taken into account. The simulation results showed that in 1973, $p(F) = 0.048$, $p(G) = 0.0016$, and $p(H) = 0.00022$. Based on the probabilities of events F and G, Fig. 2, and (6) and (8), $p(S_P) = 0.0498$ and $p(T) = 0.0500$. A probability of failure of 0.05 is very high for a bridge on a U.S. route. For major structures, such as bridges, a probability of failure on the order of 10^{-4} or 10^{-5} is desirable. As an example, the U.S. Army Corps of Engineers (USACE 1992) has determined that probabilities of failure (or unsatisfactory conditions) for inland navigation structures >0.001 will require frequent outages for repair, and at $p_f = 0.07$, extensive rehabilitation is required. For structures with even greater probabilities of failure, emergency action is required to alleviate hazards.

CONCLUSIONS

In this paper, fault tree analysis was used to show the interactions of the complex processes of erosion at bridge piers and abutments and to calculate the overall probability of bridge failure due to scour and channel instability. The advantages of using fault tree analysis for such a complex process include the following:

1. No quantitative knowledge on the interactions of the multiple processes is needed.
2. The analysis provides a probability of failure or a range of probabilities of failure based on the probabilities of individual events.
3. Although the probability of the top event [$p(T)$] is affected by the selection of the probability distributions, an exact value of $p(T)$ is generally not required, rather an order of magnitude is needed. Therefore, although the selection should be made as carefully as possible, it is not critical to the end result that the true population distribution is known. The assignment of a coefficient of variation to each random variable may have a significant impact on the resulting $p(T)$ and should be selected carefully.

Through fault tree analysis, a complex combination of processes can be examined and the probability of failure due to excessive instability or scour can be estimated. It is also possible to examine an even more complex fault tree that would include structural modes of failure, failures of various types of mitigation measures, and alternatives in design and rehabilitation. Although only three examples were given here to show the range of possible combinations of scour and channel instabilities, there are many more possibilities that could be handled by this type of analysis.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = failure due to contraction scour at abutment;
B = failure due to local scour at abutment;
b = pier width;
C = failure due to degradation at abutment;
D = failure due to channel widening at abutment;
E = event;
E = failure due to lateral migration at abutment;
F = failure due to local scour at pier;
F = Froude number;
G = failure due to contraction scour at pier;
H = failure due to degradation at pier;
I = failure due to channel widening at pier;
J = failure due to later migration at pier;
K = correction factor;
$p(\ )$ = probability of event;
Q = discharge;
S = slope;
S_A = failure at abutment;
S_P = failure at pier;
T = top event;
W = channel width;
y = flow depth;
y_0 = depth beneath bridge;
y_s = scour depth;
γ = specific weight; and
τ = shear stress.

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