Value Engineering Approach to Geologic Hazard Risk Management

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Decision makers and planners need answers to four basic questions to deal responsibly with geologic and other hazards: (a) When will the hazard occur? (b) What will happen when the hazard occurs? (c) What area will be affected? (d) What can be done to reduce the risk? A perspective for evaluating in comparable terms all hazards at a site and a means for intelligent decision making based on the evaluation is the purpose here. The value engineering approach to geologic hazard risk management (1) is a creative effort concerned with eliminating or modifying those aspects of a system that add costs without reducing risk. The model for risk management, and the risk-based framework, permit estimation of risk costs initially for the existing conditions and subsequently for the variety of alternative responses. Selection of the optimum response to a hazard usually will be based on the least cost at some acceptable level of risk. Absolute safety is not possible, and the costs of approaching absolute safety increase exponentially. Risk costs can be considered to be expected values. Investment decisions are often based on the present worth of the expected values, on the basis of annual discount or interest rates over the design life of a facility or system. Calculation of present worth values for the variety of possible risk reduction measures permits a systematic assessment of alternatives in comparable terms to facilitate decision making. The value engineering component of this approach to geologic and other hazard risk management requires an integrated, multidisciplinary effort among geologists, engineers, seismologists, meteorologists, and socioeconomists working closely with the decision makers.

The purpose of this paper is to provide a perspective for evaluating in comparable terms all hazards at a site and a means for intelligent decision making. Value engineering (VE), an appropriate hazard management approach, is an objective, systematic method of optimizing the total cost of a facility or system for a specific number of years.

Total cost means ultimate costs to construct, operate, maintain, and replace a facility or system during its design life. The VE approach is a creative effort directed toward the analysis of functions and is concerned with eliminating or modifying those aspects that add cost without adding function or, in the case of hazards, without reducing risk.

In this context a hazard is a naturally occurring or human-induced process that has the potential to cause damage to property or injury to people. Risk is exposure of something of value to a hazard. Strong earthquake shaking is an example of a natural hazard. Citizens and facilities in the cities of San Francisco, Salt Lake City, and Memphis are at risk of injury and damage owing to shaking during a future earthquake. An earthquake occurring in an uninhabited region of the world, such as the Dasht-e-Namak in east-central Iran, certainly would be regarded as a hazard. However, no facilities would be near enough to be at risk of damage. Similarly, rocks falling from steep slopes are clearly hazardous, and a substantial population can be at risk of injury on roads next to steep-cut slopes. However, in areas where no population is exposed to potential injury, no risk would be associated with the rockfall hazard.

Systematic evaluation of hazards and risks permits assessment of the costs associated with alternative responses that provide an acceptable level of risk of damage. Figure 1 is a model of geologic hazard risk management. The initial phase in the assessment is recognition of the hazard, and failing to recognize or ignoring hazards may lead to liability for damage caused by the hazards. Once hazards are recognized, they may be evaluated in terms of the frequency or probability of damage intensities. Risks may be evaluated in terms of the extent of exposure and consequence of damage. Selection of an acceptable level of risk can be very difficult and, in many cases, is a public policy issue.

Five alternative responses exist and should be assessed sequentially (see Figure 2). A segment of highway subjected to rockfall hazards provides a useful example of the five alternative responses. The first possible response is to continue current practices, and this is the so-called "do nothing" alternative. In the context of the rockfall example, continuing current practices would constitute removing rock debris from the roadway and repairing damaged pavement on an as-needed basis. It could also include settling legal claims for damage to cars or personal injury. If continuing current practices meet the risk acceptability criteria, then present-worth costs are estimated and stored for comparative purposes. If the risk acceptability criteria are not met, then the costs need not be estimated.

The second response is to modify the hazard. In the context of the rockfall example, modifying the hazard could include measures to prevent rocks from falling from the slope or to prevent rocks from falling onto the roadway. Engineering measures to accomplish such prevention could consist of bolting or strapping rocks on the slope or draping wire mesh on the slope.

The third response is to modify the system at risk. In the context of the rockfall example, modifying the system at risk could include constructing a rock deflection shed to protect the roadway from falling rocks or placing Jersey walls along the shoulder of the road to prevent rocks from rolling onto the roadway.

The fourth response is to modify system operation. In the context of the rockfall example, modifying system operation could include placing signs warning of the rockfall hazard in

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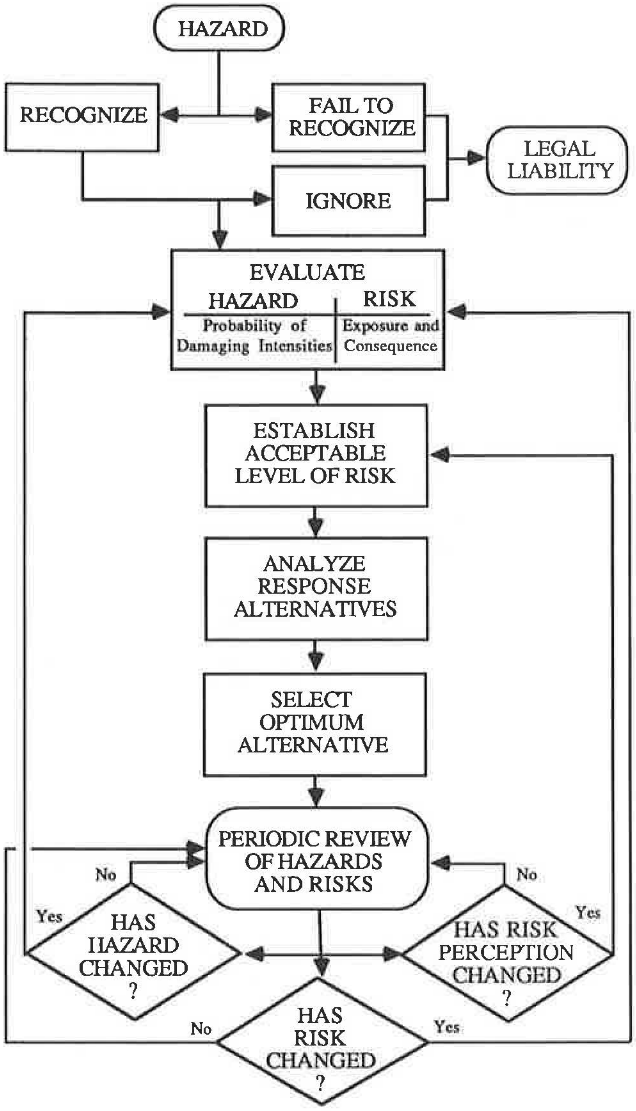

FIGURE 1 A model for geologic hazard risk management [Adapted from Keaton (*1*, p. 238).]

an attempt to get motorists to be more cautious and alert and to limit legal liability in the event of damage or injury resulting from rockfall.

If the risk acceptability criteria are not met by any of the four responses, then the acceptable level of risk may be so small that it approaches absolute safety. The fifth alternative response is to avoid the hazard regardless of the cost. In the context of the rockfall example, avoiding the hazard would require relocating an existing road or abandoning a possible alignment of a proposed road. Deciding to avoid a hazard can be particularly difficult for existing facilities that may have to be abandoned. Risk management is an iterative process with continuous checking for changes in the hazards or in the risks or the perception of acceptable risk (see Figure 1).

DECISION MAKER'S QUESTIONS

Decision makers and planners need answers to four basic questions to deal responsibly with geologic hazards.

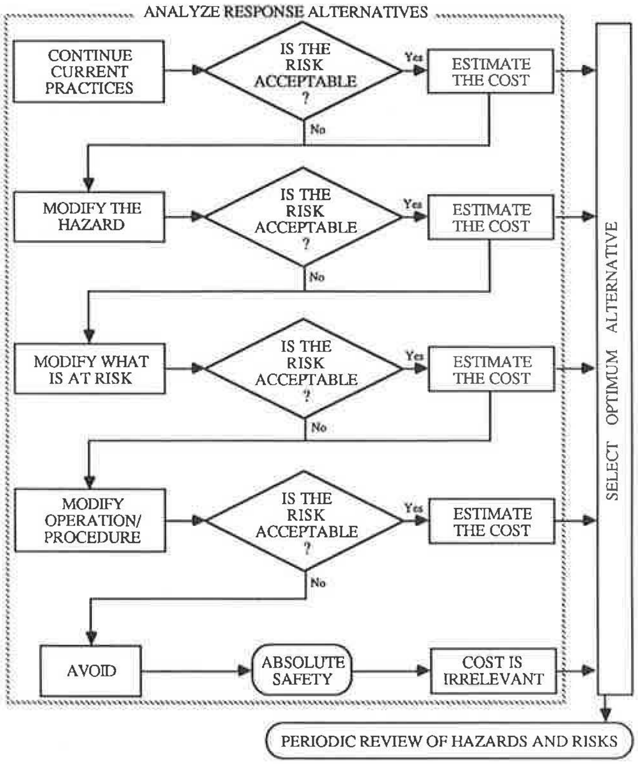

FIGURE 2 Alternative responses to geologic hazards. [Adapted from Keaton (*1*, p. 240).]

When Will the Hazard Occur?

This is a difficult question for two reasons. First, hazards are natural processes that occur at potentially damaging intensities. Second, precisely predicting the occurrence of a hazard is not presently possible. Microearthquakes and runoff from gentle rains occur frequently with no resulting damage. Major earthquakes and flooding from very heavy rains occur less frequently with some resulting damage. Intensities ranging from "no damage" to "total damage" are possible depending on the quality of construction and the character of the hazard.

Weather forecasting provides a good example of the predictability of natural processes. The traditional question "Will it rain tomorrow?" really is not the correct question for hazard analysis. A better question would be "Will a damaging flood occur tomorrow?" or "Will crops or property be damaged by a hailstorm?" Weather forecasting is based on regional weather data over the past 24 to 48 hours and on a previously developed understanding of regional weather patterns. Thus, weather forecasting is relatively easy to understand, and, in most cases, if the forecast is wrong, then no one is injured to the extent that lawsuits are filed against the forecaster. Further, weather forecasts are put in terms of probabilities (e.g., a 20 percent chance of rain tomorrow in the forecast area). The chance of rain anywhere on earth approaches 100 percent almost all the time. Such a forecast is not meaningful to most people. For example, more meaningful forecasts would describe the chance of rain along the Atlantic seaboard or, more specifically, in Washington, D.C.

Forecasting earthquakes is much more troublesome. The real question to be answered is, "When will damage occur in

St. Louis, Missouri, owing to earthquake shaking?" This question is directed at the issue of local moderate earthquakes and of distant major earthquakes. Clearly, major earthquakes in California will be too far away to cause damage in St. Louis. An adequate analysis of earthquake hazards in St. Louis needs to focus on earthquake sources within about 200 miles of the city. Earthquake hazards are evaluated by assessing historical earthquake patterns (historical seismicity) and by evaluating geologic features (faults) capable of generating earthquakes (paleoseismicity).

One of the fundamental laws of geology is called the Law of Uniformitarianism and states that processes operate today in more or less the same way as they acted throughout geologic time; that is, the present is the key to the past. This law helped early geologists interpret rock formations of sandstone and conglomerate as ancient stream channels.

The Law of Uniformitarianism needs to be amended for application to hazard analysis. The engineering geology corollary is, "The recent past is the key to the near future." Thus, for hazards such as earthquakes and landslides the geologic record must be examined for evidence that such processes occurred in the recent past (the most recent 10,000 years or more, depending on the nature of the facility). If such evidence exists, then the magnitude and frequency of such occurrences must be estimated to predict the probability that future events will occur. Those probabilities can be annualized or averaged over project lifetimes. Annual probabilities are needed by actuaries who set insurance premiums. Project life probabilities are more useful for those who make decisions about engineering design and site selection.

What Will Happen When the Hazard Occurs?

The assessment of the effects of a hazard usually is based on two other questions: (a) What has happened in similar events in the immediate area and elsewhere? (b) How fragile is the feature or structure at risk? An important issue in the context of those questions is the contrast between planned new facilities and existing old facilities. Planned facilities can be designed to accommodate the forces of infrequent hazards, but significant uncertainty commonly is associated with many design details of existing facilities.

Structural damage and damage to building components and contents are easy to visualize and to understand. An issue commonly overlooked is business interruption or loss of function. Critical facilities—those needed during and immediately following natural disasters—clearly have a smaller tolerance for interruption than do noncritical facilities. Some critical facilities are hospitals, fire stations, police stations, and schools.

What Area Will be Affected?

Damage usually is greatest close to the "center" of a hazard and diminishes with increasing distance. Flood damage usually is concentrated along the margins of stream channels. Landslide damage usually is confined to the landslide itself.

A notable exception to this generalization is the Thistle landslide, which occurred in central Utah in 1983. The landslide disrupted the ground over which a major highway and a major railroad crossed. No facilities were built on the slide mass itself. Thus, immediate damage caused by the moving earth of the landslide was restricted to a highway and a railroad. Secondary damage was caused by a lake that formed behind the landslide and dammed the Spanish Fork river. The lake inundated the small community of Thistle. The threat of tertiary damage owing to catastrophic release of water in the event the landslide dam failed was great. Thus, much money and effort were used to reinforce the landslide dam and to drain the lake. Also, the Denver and Rio Grande Western Railroad was losing approximately $1 million each day they could not use their tracks past the landslide. Coal miners in central Utah were furloughed until coal could be shipped by rail to Wasatch Front markets. Travelers were forced to go hundreds of miles out of their way because the landslide blocked the only transportation route across the northern Wasatch Plateau to central Utah. Thus, although the damage owing to primary and secondary hazards was significant, losses owing to business interruption and travel inconvenience probably were greater.

The example of the Thistle landslide clearly demonstrates that assessing the area that could be affected by a hazard is complicated, particularly when potential business interruption is included.

What Can Be Done to Reduce Risk?

The answer to the question of what can be done to reduce risk depends on the specific characteristics of the hazard, and the reader is referred to the discussion of alternative responses to hazards (Figures 1 and 2). Proposed facilities, for relatively little additional cost, can be designed to resist the forces of infrequent hazards or be located to avoid them. Conversely, existing facilities require significant additional cost to be upgraded and strengthened to resist larger forces than was originally anticipated. Further, business interruption costs can be substantial while upgrading is done. The costs of alternative responses must be compared to the probability of occurrence of hazards and the potential losses (dollar-value damage, personal injury, and business interruption). An innovative method of addressing this complicated issue is value engineering in a risk-based framework.

RISK-BASED FRAMEWORK

A risk-based method for assessing possible improvements for dam safety was developed by Bowles et al. (*2*) and consists of four elements: risk identification, risk estimation, risk aversion, and risk acceptance. Those elements, modified to reflect sedimentation hazards on arid region alluvial fans, are presented in Figure 3. The risk identification element involves listing the various factors that could contribute to potential losses and then organizing those into logical event sequences that cover all expected events and responses. Such event sequences commonly are configured into event trees that serve as risk models for evaluating existing conditions and the effectiveness of proposed mitigation or aversion alternatives. The risk estimation element involves assigning probabilities to each branch of the event tree model and then assessing the con-

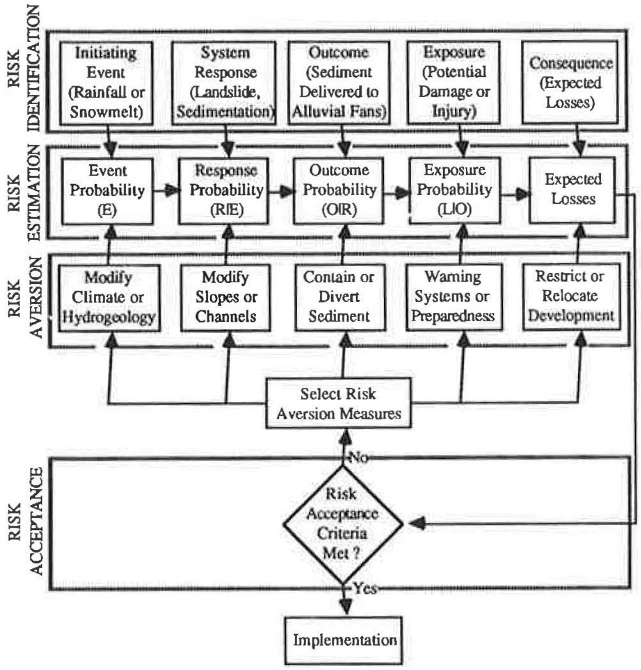

FIGURE 3 Risk-based method for assessing hazards and responses. From Keaton (*1*, p. 174) after Bowles et al. (*2*).

sequences of each event and response along separate pathways in the event tree. If the expected losses (damage or injury or both) are unacceptable under existing conditions, then some form of risk aversion may be desired to reduce the probability associated with an initiating event, a system response, or an outcome or to reduce the exposure to the hazard. (Alternative responses for dealing with hazards were described earlier and are shown in Figure 2.) The risk acceptance element is involved with deciding what degree of safety is appropriate or what residual risk will be accepted.

A complete hazard evaluation of potentially damaging processes consists of (a) identifying locations, (b) estimating frequencies, (c) estimating magnitudes, (d) estimating the rates at which they occur, (e) estimating durations, (f) estimating the certainty with which they can be forecast, and (g) estimating possible effects. Those seven components of hazard evaluation must be addressed in a quantitative way to answer the four questions just discussed.

A relationship appears to exist between frequency and magnitude. Large magnitude events (earthquakes, floods, sediment delivery) appear to occur less frequently than do small magnitude events. This relationship for sedimentation events is presented in Figure 4 in terms of annualized frequency versus event magnitude. Two types of relationships are indicated on this figure: a straight line (linear) relationship and an irregular line (nonlinear) relationship. Because the annual frequency is represented as a logarithm, the straight line relationship is actually a log-linear relationship. (Mathematical expressions can be developed to describe those relationships, but the discussion of the expressions is beyond the scope of this conceptual paper.) The important issue displayed by Figure 4 is that small events occur relatively frequently and that large events are rare. For example, an annual frequency of 1.0 (shown on the left side of Figure 4) means that events of the size corresponding to that frequency occur (or recur) on average every year (shown on the right side of Figure 4).

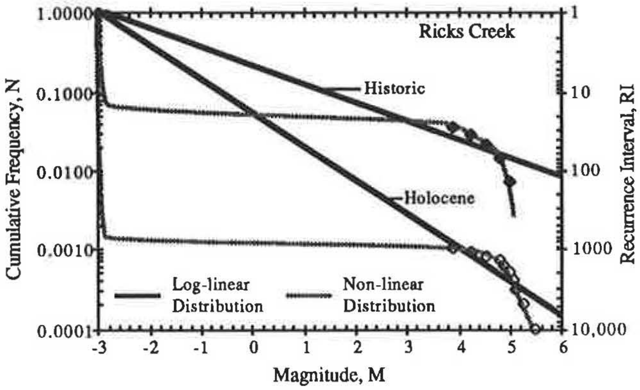

FIGURE 4 Annual frequency of sedimentation events as a function of event magnitude. Modified from Keaton (*1*, p. 394).

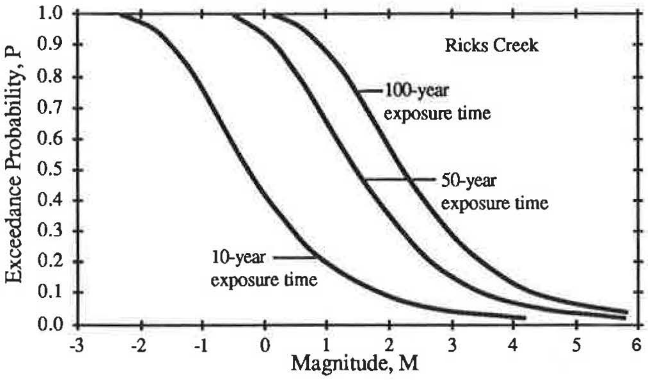

FIGURE 5 Exceedance probability curves for sedimentation events. Based on an average of the magnitude-frequency relationships shown on Figure 4. From Keaton (*1*, p. 223).

Magnitude-frequency relationships may be transformed into exceedance probabilities, as presented for sedimentation events in Figure 5. The same procedure is commonly used for earthquake or flood risk assessment. Exceedance probabilities may be developed for normal (evenly distributed about a mean value) and extreme-value (skewed about a mean value) distributions of event magnitudes. Detailed discussion of those distributions of event magnitudes is beyond the scope of this paper, but a brief description is presented in the Appendix. However, knowledge of those distributions is needed for quantitative estimation of probabilities needed in risk evaluation.

The risk estimation element of the method developed by Bowles et al. (*2*) (see Figure 3) is expressed in terms of the probabilities of events, responses, and outcomes. Their risk model is in the form of an event tree with a number of pathways that represent an outcome associated with a response to an event. For an event tree with *n* possible mutually exclusive pathways, Bowles et al. (*2*, p. 216) report that the pathway probability for the *i*th pathway is

$$P(Pi) = P(E)P(R|E)P(O|R) \qquad (1)$$

where $P(Pi)$ is the pathway probability for the ith pathway, $P(E)$ is the probability that event E will occur, $P(R|E)$ is the conditional probability that response R will occur given that event E occurs, and $P(O|R)$ is the conditional probability that outcome O will occur given that response R occurs. The partial risk cost for the ith pathway is

$$C(Pi) = P(Pi) \cdot Le \tag{2}$$

where Le is the possible economic loss. The total risk cost (C) is obtained by summing the partial risk costs over all n mutually exclusive pathways in the event tree or

$$C = \sum_{i=1}^{n} C \cdot (Pi) \tag{3}$$

For a population at risk (PAR), the magnitude of life loss (Ll) owing to events along the ith pathway is given by

$$\mathrm{Ll} = P(L|O) \cdot \mathrm{PAR} \tag{4}$$

where $P(L|O)$ is the conditional probability of life loss L given that outcome O occurs.

An example of a hypothetical event tree for earthquake-induced rockfall damage to a highway is presented in Figure 6. The initiating event (see Figure 3) is an earthquake subdivided into three magnitude ranges. The event probabilities $[P(E)]$, annualized in this example, are developed from analyses similar to those shown in Figures 4 and 5. In this simplified example, each of the three event magnitude ranges has five possible system responses, resulting in 15 possible pathways. However, only those five pathways related to the middle event magnitude are presented in Figure 6. The annualized conditional probabilities for system response given the initiating event $[P(R|E)]$ are estimated on the basis of past performance of, in this example, the slope above the highway. The occurrence of a rockfall or slope failure does not necessarily imply damage to a system or a facility at risk. Therefore, each of the 15 possible system response pathways has five possible outcome pathways, resulting in 75 possible pathways. However, only those five pathways related to the middle response are presented in Figure 6. The annualized conditional probabilities for outcome given the system response $[P(O|R)]$ are estimated on the basis of the geometry and past performance of the slope, the location of the highway, and the possibly seasonal aspect of slope performance (e.g., an earthquake occurring during or shortly following the rainy season).

Annualized pathway probabilities $[P(Pi)]$ are the product of the individual annualized probabilities just described. Possible economic loss [Le] in this example is restricted to capital cost of reopening the road and repairing damage. Many other costs, much more difficult to estimate than repair costs (e.g., business interruption costs), would be considered in an actual probabilistic evaluation of the risk of damage to a highway. The partial annualized risk costs $[C(Pi)]$ are the product of the possible economic losses and the pathway probabilities. The total annualized risk cost is the sum of the partial risk costs for all 75 mutually exclusive pathways in this simplified example.

PROBABILISTIC EVALUATION

The probabilistic analysis to this point has focused on the probabilities and costs of individual components of potential hazard occurrences. Similar event trees as those presented in Figure 6 would be developed for the variety of possible hazards (nonearthquake landslides, flooding, hail storms, wind storms). Decisions must be made about dealing with the hazards, and probabilistic methods provide the basis for such decisions.

Earthquake and flood hazards commonly are evaluated on the basis of the probability that a certain size of event will be equalled or exceeded in a specified period of time, known as exceedance probability. The specified period of time represents an exposure time and commonly is called a "design life" or an "economic life" for the facility or feature under consideration. Earthquake engineering commonly employs two levels of "design" earthquake events: a lower-level event (LLE) and an upper-level event (ULE). The LLE is an event that has a relatively high probability of occurring during the design life, and the ULE has a relatively low probability. Consequently, the LLE has a smaller magnitude (hence, lower level) than does the ULE (hence, upper level). Typical design lives range from as little as 10 years to as much as 100 years or more, depending on the critical or noncritical nature of the facility. Commonly accepted probabilities for design range

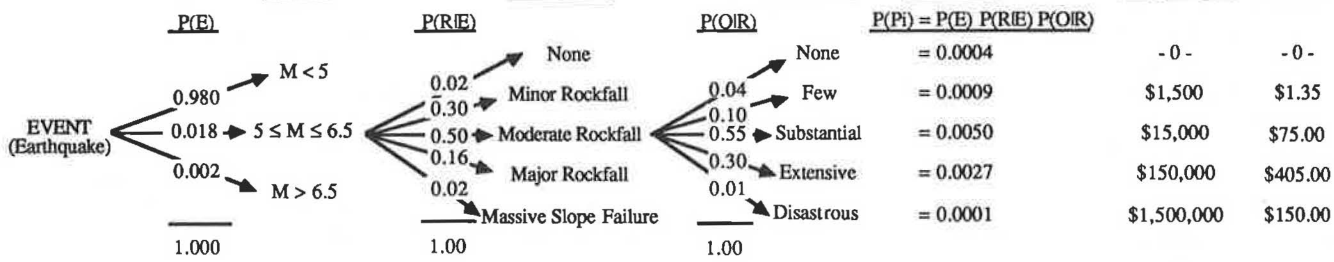

FIGURE 6 Part of a hypothetical event tree for earthquake-induced rockfall damage to a highway.

from 50 to 10 percent. For example, the LLE usually is taken as the earthquake acceleration that has a 50 percent probability of being equalled or exceeded during a 50-year period, and the ULE has a 10 percent probability in the same 50 years. Urban flood hazards commonly are evaluated in the context of the "100-year" floodplain, which is that area with an annual probability of 0.01 that it will be inundated by flood waters. A "100-year" flood has a probability of 0.63 of occurring during a 100-year design period or 0.39 of occurring during a 50-year design period.

It is at this point that a most difficult question must be addressed: How safe is safe enough? This question commonly is not addressed uniformly with respect to a variety of hazards. Usually only those hazards regulated (e.g., floods and earthquakes) are considered. Consequently, a de facto acceptance of risk, even if the risk is unacceptable, results for those hazards not considered specifically. Therefore, systematic assessment of all hazards and alternative responses promotes intelligent decision making.

VALUE ENGINEERING APPROACH

The value engineering approach to geologic hazard risk management described by Keaton and Eckhoff (*3*) is a creative effort concerned with eliminating or modifying those aspects of a system that add cost without reducing risk. The model for risk management (Figures 1 and 2) and the risk-based framework (Figure 3) permit estimation of risk costs initially for the existing conditions and subsequently for the variety of alternative responses. Selection of the optimum response to a hazard normally will be based on the least risk at the least cost. Absolute safety is not possible, and the cost of approaching absolute safety increases exponentially. (This concept is portrayed schematically in Figure 7.) The annualized risk cost is optimized for a hazardous event that has a moderate probability of occurring and a moderate cost of potential losses. This is true because higher costs of potential losses correspond to low probabilities of occurrence, and higher probabilities correspond to low potential costs. This can be seen in the partial risk cost column in Figure 6.

The risk costs can be considered to be expected values. Investment decisions usually are based on the present worth of the expected values. Present worth (PW) is calculated on the basis of annual discount or interest rates (i) over the period of time of interest or the design life of a facility or system (t) in the following way:

$$PW = \sum_{n=1}^{t} (CEV)\cdot(1 + i)^{-n} \qquad (5)$$

where CEV is the annualized expected value of the risk cost and n is incremented 1 year at a time for the total facility life. Calculation of present worth values for the variety of possible risk reduction measures permits a systematic assessment of alternatives in like terms that can facilitate decision making. Similar calculations can be made for the present worth of future operating and maintenance costs.

The value engineering approach to geologic hazard risk management requires an integrated multidisciplinary effort among geologists, engineers, seismologists, meteorologists, and socioeconomists working closely with decision makers.

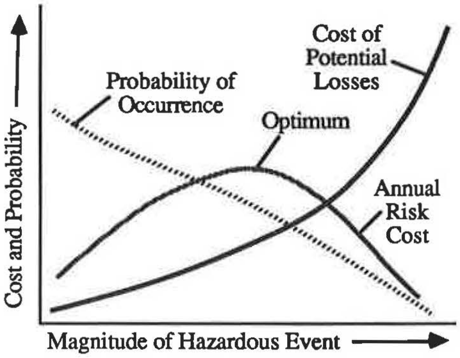

FIGURE 7 Schematic diagram showing optimization of annualized risk cost.

APPENDIX

The annual frequency of sedimentation events at Ricks Creek, Davis County, Utah, presented on Figure 4, was calculated on the basis of observations of the number and size of the events deduced from geomorphic expression and stratigraphy of the alluvial-fan deposits. Two distributions are shown on Figure 4 for two time frames. The two distributions are log-linear and non-linear. The two time frames are historic (the past 140 years in this part of the Wasatch Front in north-central Utah) and Holocene (approximately the past 10,000 years, or post-Lake Bonneville time). The sediment discharge events shown on Figure 4 are listed in Table A1.

Cumulative frequencies, NPR, were calculated by the Weibull plotting position formula:

$$NPR = \frac{Re}{(PR + 1)} \qquad (A1)$$

where Re is the event rank and PR is the period of record. The sediment event volume was converted to an event magnitude by defining magnitude M as a dimensionless parameter:

$$M \equiv \log \frac{V}{Vo} \qquad (A2)$$

where V is the event volume in m^3 and Vo is 1 m^3. The mean log-linear relationship for the historic data at Ricks Creek is

$$\log N_{PR} = -0.674 - 0.236 \cdot M$$
$$(n = 6; r^2 = 0.951) \qquad (A3)$$

and for the Holocene data is

$$\log N_{PR} = -1.255 - 0.432 \cdot M$$
$$(n = 11; r^2 = 0.975) \qquad (A4)$$

The nonlinear relationship is manipulated with extreme-value statistics (*4*) and is based on the mean and standard deviation of the sample population along with reduced extreme-

TABLE A1 SUMMARY OF SEDIMENT DELIVERY EVENTS AT RICKS CREEK FAN, DAVIS COUNTY, UTAH

Year	Volume (m^3)	Magnitude ($\log\frac{V}{V_o}$)
Prehistoric	315,000	5.50
Prehistoric	183,000	5.26
Prehistoric	132,000	5.12
Prehistoric	118,000	5.07
Prehistoric	80,000	4.90
1923	72,000	4.86
1930	100,000	5.00
1932	34,000	4.53
1934	22,000	4.34
1983	8,000	3.90

value mean and standard deviation. All years during the 140-year historic period in Davis County without documented sediment delivery were assumed to have actually experienced 0.001 m^3 of sediment ($M = -3$). The historical mean magnitude at Ricks Creek was calculated to be -2.731 with a standard deviation of 1.404. Gumbel's (*4*, p. 228) reduced extreme-value mean for $n = 140$ is 0.56369 with a standard deviation of 1.22157.

Exceedance probabilities were evaluated with binomial and Poisson statistics for the Holocene period and with extreme-value statistics for the historical period. The results of those two methods of analysis were averaged and presented in Figure 5. The different methods of analysis were believed to better represent reality, as described by Keaton (*1*). The binomial and Poisson methods gave results that were not statistically different. The binomial exceedance probability relationship is

$$P(e \geq M, t) = 1 - (1 - N_{\mathrm{PR},M})^t \tag{A5}$$

where $P(e \geq M, t)$ is the exceedance probability that an event e will equal or exceed a magnitude M in a period of time t, and $N_{\mathrm{PR},M}$ is the annual frequency of events of magnitude M in a period of record PR. Thus, Equation A4 can be solved for N_{PR} as a function of M:

$$N_{\mathrm{PR}} = 10^{(-1.225 - 0.432M)} \tag{A6}$$

The extreme-value exceedance probability relationship is

$$P(e \geq M, t) = 1 - e^{-te^{-A(M-U)}} \tag{A7}$$

where

$$A = \left(\frac{\sigma_G}{\sigma_M}\right) \tag{A8}$$

$$U = \mu_M - \left(\frac{\mu_G}{A}\right) \tag{A9}$$

where μ_G and σ_G are the mean and standard deviation of the reduced extreme value for the period of record and μ_M and σ_M are the mean and standard deviation of the observations that are reported for Ricks Creek.

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