EVALUATION AND ACCEPTANCE OF RISK IN GEOTECHNICAL ENGINEERING

by

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INTRODUCTION

During the past few years, there has been a growing interest by geotechnical engineers in the use of risk-based procedures not only as a tool for assessing uncertainties but also as a means of establishing acceptability of risks. At the same time, legal interpretation of geotechnical engineers' responsibilities has provoked a much greater awareness of the need to communicate the extent of risk and uncertainty involved in a project or facility to the client/owner.

This paper presents a fundamental risk-based approach to developing and presenting quantified measures of risk which can be compared with common "yard-sticks" of acceptability. The approach can be used in many types of geotechnical projects where uncertainty cannot be economically eliminated. The versatility of the method will first be demonstrated by a simple example of rockfall and rock slides threatening a subdivision. An example of a more comprehensive and complicated analysis of risk to dams will then be given.

BRIEF DESCRIPTION OF METHOD

Risk assessment first involves the identification and evaluation of risks associated with a project. These first two steps are normally performed by an analyst, in this case a geotechnical engineer. The acceptance of risk or of mitigation or avoidance is usually the responsibility of owners and regulatory bodies and may well involve political judgments. A detailed description of the identification-evaluation-acceptance-mitigation cycle in landslide hazard analysis has been given by Pack and Morgan (1987).

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From the standpoint of major civil works, risk is measured in terms of potential fatalities and property damage. As discussed later, it is important to distinguish between risk to the individual (expressed as the probability of the death of an individual per annum or PDI) and risk to a population or group of individuals (expressed as the probable number of deaths per annum or PND). Finally, risk to property is most easily expressed as the "annual risk cost" or ARC.

In order to measure or quantify risk, the analyst must first identify the various sequences of events which can lead to a loss of life or property. Beginning with a triggering event (e.g. an earthquake), consequential events can follow various paths to a possible loss (e.g. a drowning). Unlike dominos where one is assured that each tile when hit by the next will fall, each successive event has a probability associated with it that accounts for the uncertainty as to whether or not a drowning will in fact follow from an earthquake. These linkages can be broken down into categories of successive steps which can be remembered by the acronym: "T.R.O.E.L" signifying Trigger, Response, Outcome, Exposure, Loss. In other words, a "trigger" such as an earthquake can lead to a "system response" including liquefaction of the foundation soil. This in turn may lead to an "outcome" such as an earth dam embankment failure. Depending on the "exposure" including the location of a town downstream or even time of day this could lead to a "loss" such as a drowning. Thus the evaluation of risk requires estimating the probability that each event in a chain or linkage will in fact occur.

Before discussing specific formulas used in evaluating risk, we must first introduce the form of notation. For example, $P(R|T)$ represents the probability P that an unfavourable response R will happen <u>given</u> a trigger T occurs. The symbol "¦" represents the word "given".

The annual risk cost (ARC) can be calculated using the following formula:

$$ARC = P(T) \times P(R|T) \times P(O|R) \times P(E|O) \times P(L\$|E) \times L\$ \quad \ldots\ldots(1)$$

In this case, $L\$$ is the loss in terms of dollars. Similarly, the probable number of deaths per annum (PND) of a population can be calculated by:

$$PND = P(T) \times P(R|T) \times P(O|R) \times P(E|O) \times P(L^*|E) \times L^* \quad \ldots\ldots(2)$$

where L^* is the number of deaths given the chain of events in fact occurs. Finally the probability of death per annum for an individual (PDI) can be calculated by:

$$PDI = P(T) \times P(R|T) \times P(O|R) \times P(E|O) \times P(L^I|E) \quad \ldots\ldots(3)$$

which is the same as the first two formulas except that the final loss term is eliminated and L^I represents the loss of one individual.

The probability terms listed above can be split apart or combined to fit the case. For example, recognizing that sometimes only partial liquefaction occurs, it may be desirable to expand the analysis of liquefaction R leading to dam failure O to include the probability that an embankment failure R_2 caused by liquefaction R leads to a dam failure O. In this case the terms $P(R_2|R)$ and $P(O|R_2)$ replace the term $P(O|R)$ in the above formulas. The following formula is an example of how terms can be combined:

$$P(R) = P(T) \times P(R|T) \qquad \ldots\ldots(4)$$

If, as in our example, the probability of liquefaction can be calculated directly, the terms can be combined as in Equation 4 to eliminate any consideration of the trigger mechanism T.

It is often convenient to deal with "expected losses" in an analysis. The last two terms in Equations 1 and 2 when multiplied give the expected loss given a certain exposure $EX(L|E)$ or in formula form:

$$EX(L|E) = P(L|E) \times L \qquad \ldots\ldots(5)$$

Likewise, the last three terms in Equations 1 and 2 can be combined if expected losses given an outcome $EX(L|O)$ are to be calculated. Examples of the use of some of these combinations will be given in the following case histories.

Given these simple formulas, the task then becomes one of identifying the chain of events and then estimating the individual probabilities for each event.

EVENT TREES AND CALCULATION TABLES

Often the evaluation of total risk involves considering several linkages with different types of events at different magnitudes. In this case, the simple formulas described above must be used for each possible linkage. The list of possible events in a linkage are usually first compiled in the form of an event diagram, an example of which is given in Figure 1. In this case arrows are drawn to show possible linkages of events. An event tree is then developed which allows a more accurate definition of the actual linkages (branches of the tree) which should be analyzed. Figure 2 is an example of an event tree which corresponds to Figure 1. Both of these figures show how individual events in a chain can be of different categories as well as magnitudes.

The total risk is calculated by applying Equations 1, 2 and 3 to each branch in Figure 2 and summing the resulting values.

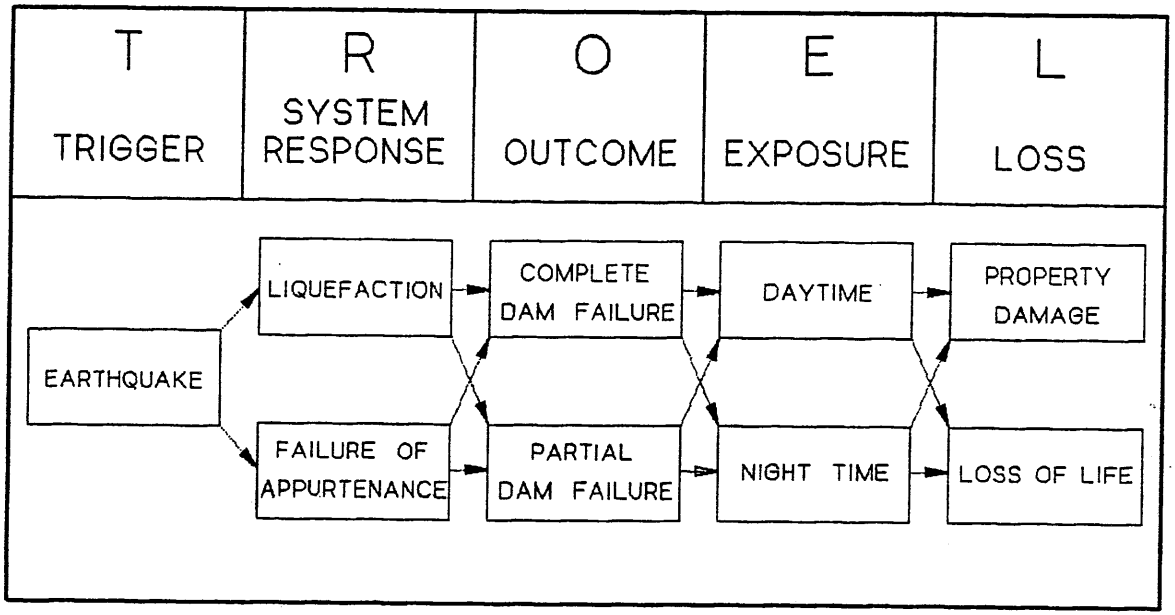

Figure 1. Example of an Event Diagram used in risk analysis

To facilitate risk calculations, each branch of the event tree is treated as a separate row in a calculation table. Table 1 shows diagrammatically how probability terms can be combined in an analysis. A brief description of the probability theory behind these diagrams and table is found in the Appendix.

The detail to which each possible chain of events is identified and evaluated depends on the intended application of the risk assessment. Usually the analysis is limited to those chains of events which are most probable or which can be analytically estimated. These linkages are then tabulated, as in Table 1, and the probabilities in each row are multiplied to obtain either ARC, PND or PDI for each linkage. The results for each linkage are then added to obtain the total risk.

The risk calculation table is also useful for performing a sensitivity analysis. Uncertain probability estimates can be varied to determine what effect they have on the total risk estimate. Where large effects are found, additional effort to reduce the amount of uncertainty should be considered. This may result in adopting a more conservative design. The table is also useful for determining which events (trigger, system response, outcome, exposure or loss) will result in the largest reduction in total risk when mitigated. Examples of these uses will be presented in the next section.

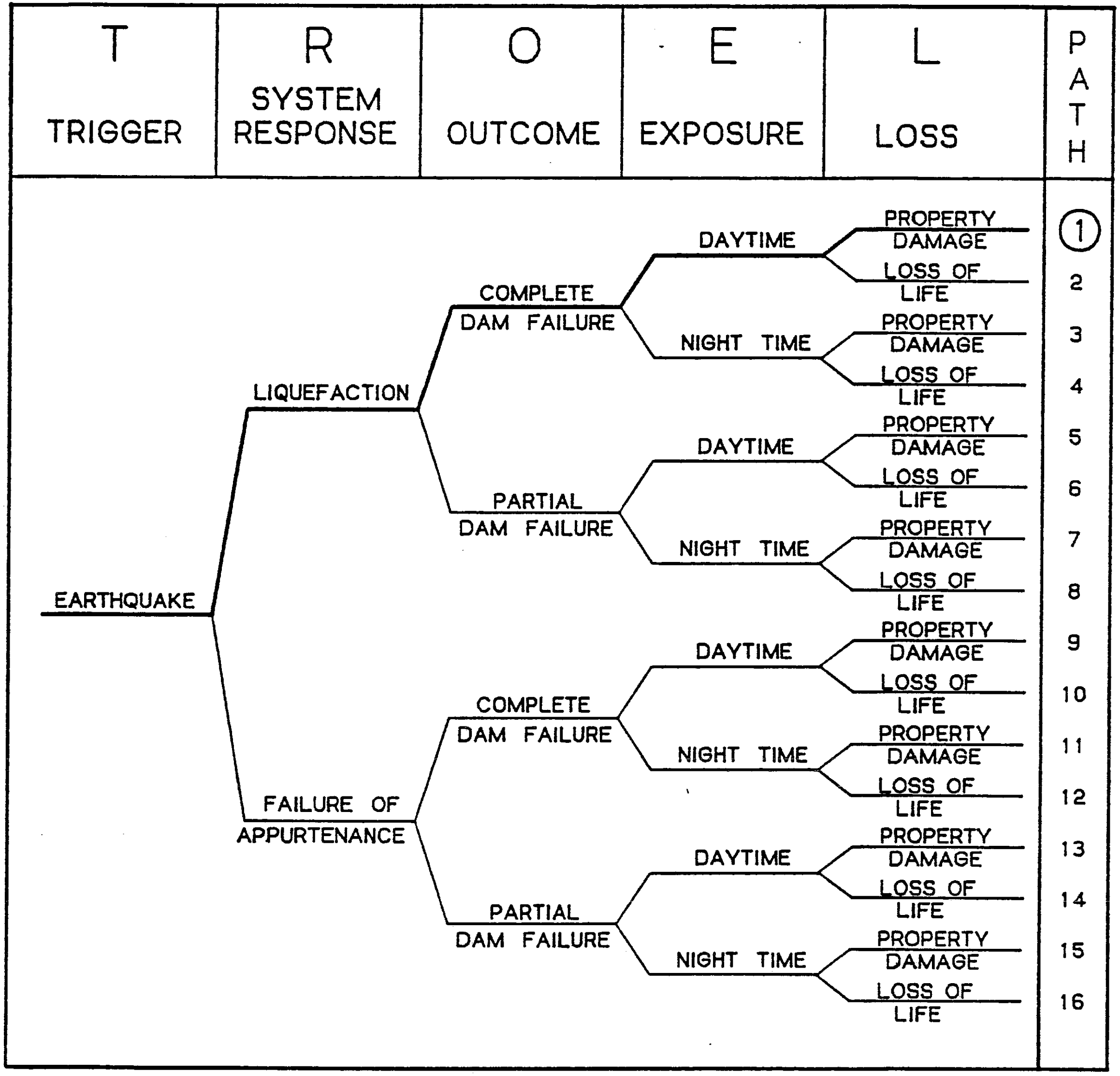

Figure 2. Example of an event tree used in risk analysis. The linkage marked with a heavy-weight line is used as an example in Table 1.

RISK CALCULATION METHODS

The individual probabilities of occurrence of each event in a linkage are fundamentally either time-dependent or conditional. By necessity, the first probability in the linkage is time-dependent. For example, the probability of an earthquake or probable maximum flood is usually expressed in terms of recurrence interval or return period. Subsequent event probabilities are not time-dependent as they are conditional on the previous event occurring. If one is able to calculate a time-dependent probability further down the chain than at the trigger (T) level, the analysis is simplified as the number of linkages which need to be assessed is greatly

Table 1. General form of Risk Calculation Table with an example of various analyses for dam safety.

PROBABILITY OF					ACTUAL LOSS	ARC	PND	PDI
TRIGGER	RESPONSE	OUTCOME	EXPOSURE	LOSS				
EARTHQUAKE $P(T)$	Probability of LIQUEFACTION given EARTHQUAKE × $P(R\|T)$	Probability of DAM FAILURE given LIQUEFACTION × $P(O\|R)$	Probability of DAYTIME given DAM FAILURE × $P(E\|O)$	Probability of LOSS given DAYTIME × $P(L\|E)$	$ or LIVES × L	ANNUAL RISK COST = ARC	PROBABLE NUMBER OF DEATHS or PND	PROBABILITY OF AN INDIVIDUAL DEATH
Probability of LIQUEFACTION $P(R)$		× $P(O\|R)$	× $P(E\|O)$	EXPECTED LOSS given FAILURE IN DAYTIME × $EX(L\|E)$		= ARC	or PND	PDI
$P(T)$	Probability of DAM FAILURE given EARTHQUAKE × $P(O\|T)$		Probability of LOSS given DAM FAILURE × $P(L\|O)$		× L	= ARC	or PND	PDI
Probability of DAM FAILURE $P(O)$			Expected LOSS given DAM FAILURE × $EX(L\|O)$			= ARC	or PND	PDI

TOTAL ANNUAL RISK COST = $\sum$ ☐

TOTAL PROBABLE NUMBER OF DEATHS = $\sum$ ☐

TOTAL PROBABILITY OF AN INDIVIDUAL DEATH = $\sum$ ☐

reduced. An example of this will be given with the rockfall analysis case-history in the following section.

The most common method of estimating time-dependent probabilities is by inference from historical data using empirical analyses. Probabilities of triggering events (T) such as floods, rainfall and earthquakes are commonly analyzed using historical frequency data. Records of past system responses (R) such as liquefaction or outcomes (O) such as a debris torrent or dam failure can also be analyzed if such data relates specifically to the project. For example, the average probability of dam failure could be calculated using historical failure records of similar dam types and foundations. However, if one is interested in the safety of a particular dam relative to other dams, this historical data may be of limited use. On the other hand, examination of geologic evidence of outcomes (O) at a site including such things as avalanches or rockfalls may greatly facilitate a risk assessment. Such data helps avoid the necessity of calculating probabilities associated with the climatologic and slope conditions which lead to each outcome.

The larger and more reliable the data set, the more reliable the inferred probabilities are likely to be. The geotechnical engineer should be aware of the limitations of extrapolating probabilities beyond the time periods and coverage of available data or the calculation of probabilities using faulty data.

Conditional probabilities are commonly calculated using analytical methods as they are not time dependent. For example, given an outcome (O) such as dam overtopping, dam breach analyses (Fread, 1985) and flood routing (Rae and Hurndal, 1986) can be used to estimate the likely path of downstream flooding and hence the probability that downstream residents will be exposed (E) to the hazard. Another example is the use of probabilistic liquefaction analysis (Liao et al., 1988) to determine the probability of liquefaction (R) given an earthquake (T) producing a particular acceleration. Given liquefaction (R) occurs, the probability of slope failure (O) can be calculated using a probabilistic slope stability analysis (Sharp et al., 1981).

TWO CASE HISTORIES

Though several examples of the use of this risk-based procedure exist in the general literature, few geotechnical applications have been published. This paper will give two examples: (1) evaluation of risk from rockfalls and rock slides at Silverhope B.C. based on a study by Thurber Consultants Ltd., and (2) evaluation of risk of dam failure using a hypothetical example cited by U.S. Bureau of Reclamation. To our knowledge, this method has not been used to analyze dam safety in B.C.

ROCKFALL RISK ANALYSIS AT SILVERHOPE, B.C.

The community of Silverhope, B.C. is located on an alluvial fan in front of a deltaic terrace. Immediately beyond the terrace, cliffs composed of massive intrusive rock rise to a height of 600 m. Extensive talus deposits and boulder fields at the base of the cliffs testify to rockfall activity though the slopes are heavily forested and no accidents involving rockfall have been reported. The site has been settled since the 1950's and no extensive historical record is available.

The deltaic terrace deposited beyond the talus slope during the last glacial period is believed to be at least 10,000 years old and is essentially free of boulders from rockfall. This area outside the well defined boulder deposit limits therefore is assumed to have a probability of less than 1:10,000 or 0.0001 of being reached by rock fall.

On the other hand, the talus slopes themselves were found to be subject to rockfall. The probability of rockfall reaching the talus slope zone is assumed to 1:1 or 1.00.[1].

Between the talus slope and the deltaic terrace is the rockfall shadow zone. This zone, which falls within an area beneath a line projected at a slope of 27.5° from the talus apex (Hungr and Evans, 1988), could be affected by rolling boulders. It is estimated that the probability of boulders reaching this shadow zone is moderately high, meaning that it should be assumed that an event will occur within the life span of a house or a similar structure. This is equivalent to an annual probability of about 1:100 or 0.01.

Three rock slides involving debris volumes up to 20,000 m^3 have occurred on the site between 1000 and 10,000 years ago. The debris from these slides did not reach beyond the present talus limits. The annual probability of future slides of this nature occurring in the area is therefore taken to be of the order of 1:5,000 or 0.0002.

Given the above-noted observations of rockfall, and considering the proximity of housing development within the hazard zones, an event diagram can be constructed as shown in Figure 3. Note that the triggering events (frost wedging and earthquakes) are initially included in the diagram though they are not later analyzed as separate probabilities. The rock slide hazard, because of its size, results in a higher exposure of buildings. This higher magnitude is treated as a separate event. Figure 4 shows the event tree for the study

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[1] A much more detailed analytical procedure for estimating rockfall probabilities on a talus cone has been developed by Hungr, 1988).

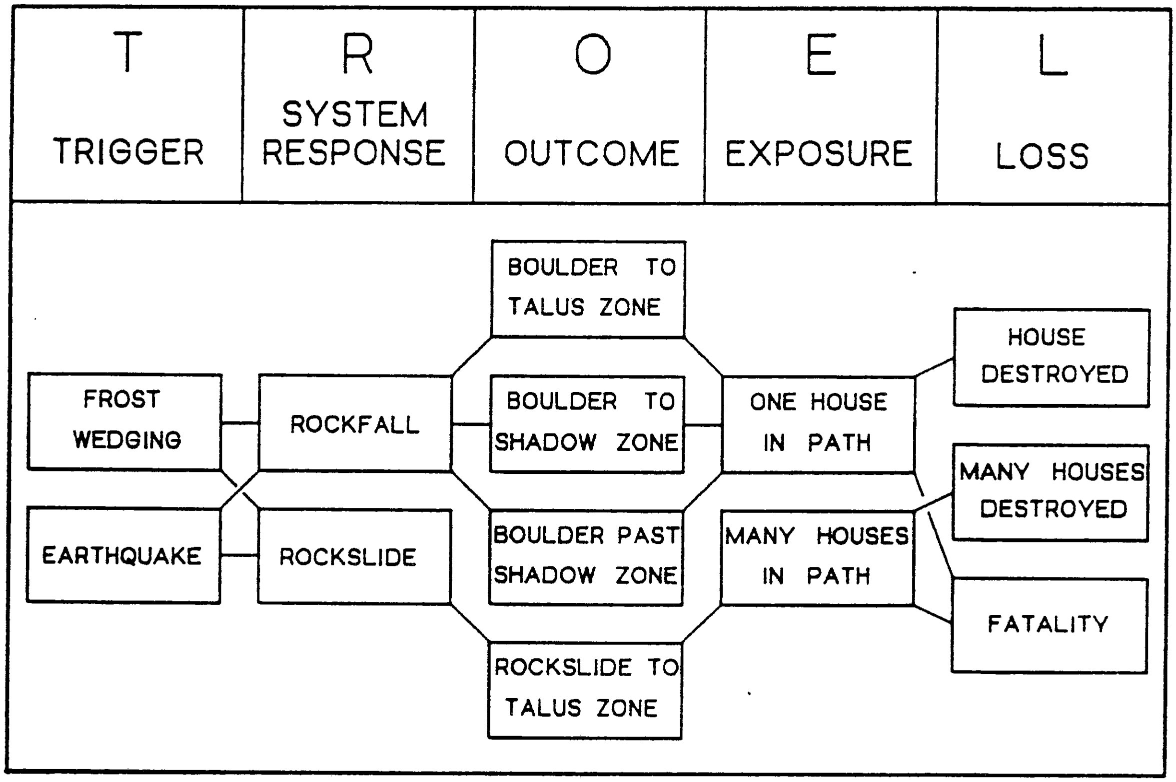


Figure 3. Event diagram for Silverhope hazards study.

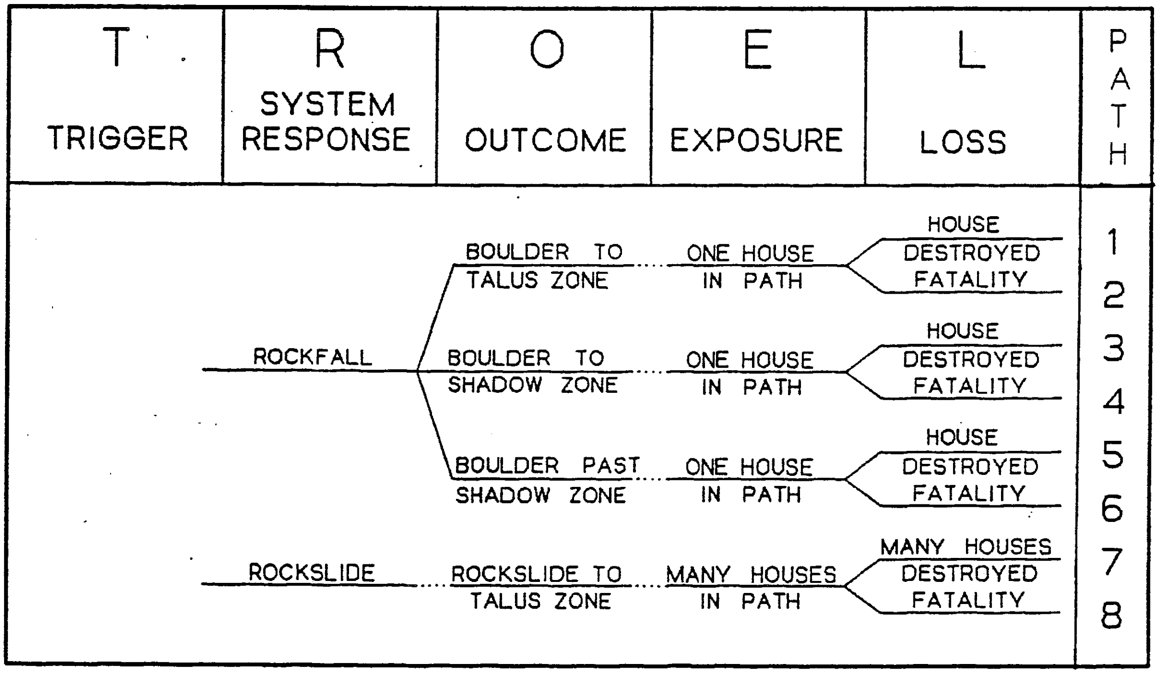


Figure 4. Event tree for Silverhope hazards study.

with numbers corresponding to each event linkage. These numbers correspond to each row of the risk calculation table shown in Table 2.

Table 2 shows how the estimates of rockfall and rock slide probabilities discussed above are entered as outcome probabilities P(O) because it was not practical to analyze the probability of triggering events P(T) or system responses P(R).

Exposures to rockfall were calculated as the total width of buildings exposed to the upslope areas within a hazard area divided by the total length of the hazard zone perpendicular the fall-line of the slope. The 224 buildings found in the area beyond the rockfall shadow account for the relatively high probability of impact given a rockfall enters this zone P(E¦O) of 0.706. As only 3 and 14 buildings lie within the talus and rockfall shadow zones respectively, the values of P(E¦O) are correspondingly lower.

Given a rock hits a house, it is assumed that the impact will cost about $100,000. This assumption is thought to be reasonable as the size of boulder required to reach the residential areas will likely be large enough to cause considerable damage. It is also estimated that on the average, there is a 50% chance that 2 people will be in the house when it is hit and be killed.

Table 2 also illustrates the exposure of a select individual is normally much lower than the population at large. In this case history, the individual is concerned only with his house and whether he is in it at the time of a rockfall or slide. This results in a lower PDI for the individual. For example, when considering the prospect of a boulder going beyond the rockfall shadow (linkage 6, Table 2), the PDI is estimated to be approximately 2 X 10^{-7} as compared to a PND value estimated at 7.1 X 10^{-5}. The total risk for a select individual is also calculated somewhat differently. Since the individual can only be in one place at any given time, only the PDI values from different hazard zones are summed.

The total annual risk cost is found to be $952. Interestingly, it is also found that $900 of the $952 is due to the risk to the 3 houses within the talus zone. Though the exposure probability is much less in the talus zone than the other hazard zones due to the low number of houses, the high outcome probability more than compensates to make this zone the most likely to receive losses from rockfall damage. A similar result is found with respect to loss of life. The analysis yields a total annual probability of an individual death of 1:210 and a probable number of deaths per annum of 0.00953. The use of these results to judge acceptability is discussed in Section 6.

Table 2. Risk calculation table for Silverhope hazards study.

LINKAGE NUMBER	P(O)			EX(L¦O)			ARC	PND (X10^{-3})	TALUS ZONE PDI (X10^{-3})	SHADOW ZONE PDI (X10^{-3})	BEYOND SHADOW PDI (X10^{-3})
	P(T)	P(O¦T)		P(L¦O)		L					
	P(R)		P(O¦R)	P(E¦O)	EX(L¦E)						
	P(T)	P(R¦T)	P(O¦R)	P(E¦O)	P(L¦E)	L					
1	BOULDER REACHES TALUS ZONE 1.00			HOUSE IN PATH Ep=0.009	HOUSE DESTROYED 1.00	$100,000	$900				
2	BOULDER REACHES TALUS ZONE 1.00			HOUSE IN PATH Ei=0.003 Ep=0.009	FATALITY OCCURS 0.50	1 PERSON 2 PERSONS		9.00	1.5		
3	BOULDER REACHES ROCKFALL SHADOW 0.01			HOUSE IN PATH Ep=0.045	HOUSE DESTROYED 1.00	$100,000	$45				
4	BOULDER REACHES ROCKFALL SHADOW 0.01			HOUSE IN PATH Ei=0.0032 Ep=0.045	FATALITY OCCURS 0.50	1 PERSON 2 PERSONS		0.450		0.016	
5	BOULDER GOES BEYOND ROCKFALL SHADOW 0.0001			HOUSE IN PATH Ep=0.706	HOUSE DESTROYED 1.00	$100,000	$7.06				
6	BOULDER GOES BEYOND ROCKFALL SHADOW 0.0001			HOUSE IN PATH Ei=0.0032 Ep=0.706	FATALITY OCCURS 0.50	1 PERSON 2 PERSONS		0.071			0.00032
7	SMALL ROCKSLIDE REACHES TALUS ZONE 0.0002			HOUSE IN PATH Ep=0.032	HOUSE DESTROYED 1.00	$100,000	0.32				
8	SMALL ROCKSLIDE REACHES TALUS ZONE 0.0002			HOUSE IN PATH Ei=0.032 Ep=0.032	FATALITY OCCURS 1.00	1 PERSON 6 PERSONS		0.0384	0.0064		

Total annual risk cost = $952.38

Probable number of deaths per annum = 9.5594 x10^{-3}

Total annual risk to individual in talus hazard zone = 1.5064 x 10^{-3}
or about 1:650

Total annual risk to individual in rock shadow hazard zone = 0.016 x 10^{-3}
or about 1:6000

Total annual risk to individual beyond rock shadow hazard zone = 0.00032 x 10^{-3}
or about 1:300,000

Ep = Exposure to a population, i.e. to any house or individual in a hazard zone
Ei = Exposure to a particular individual.

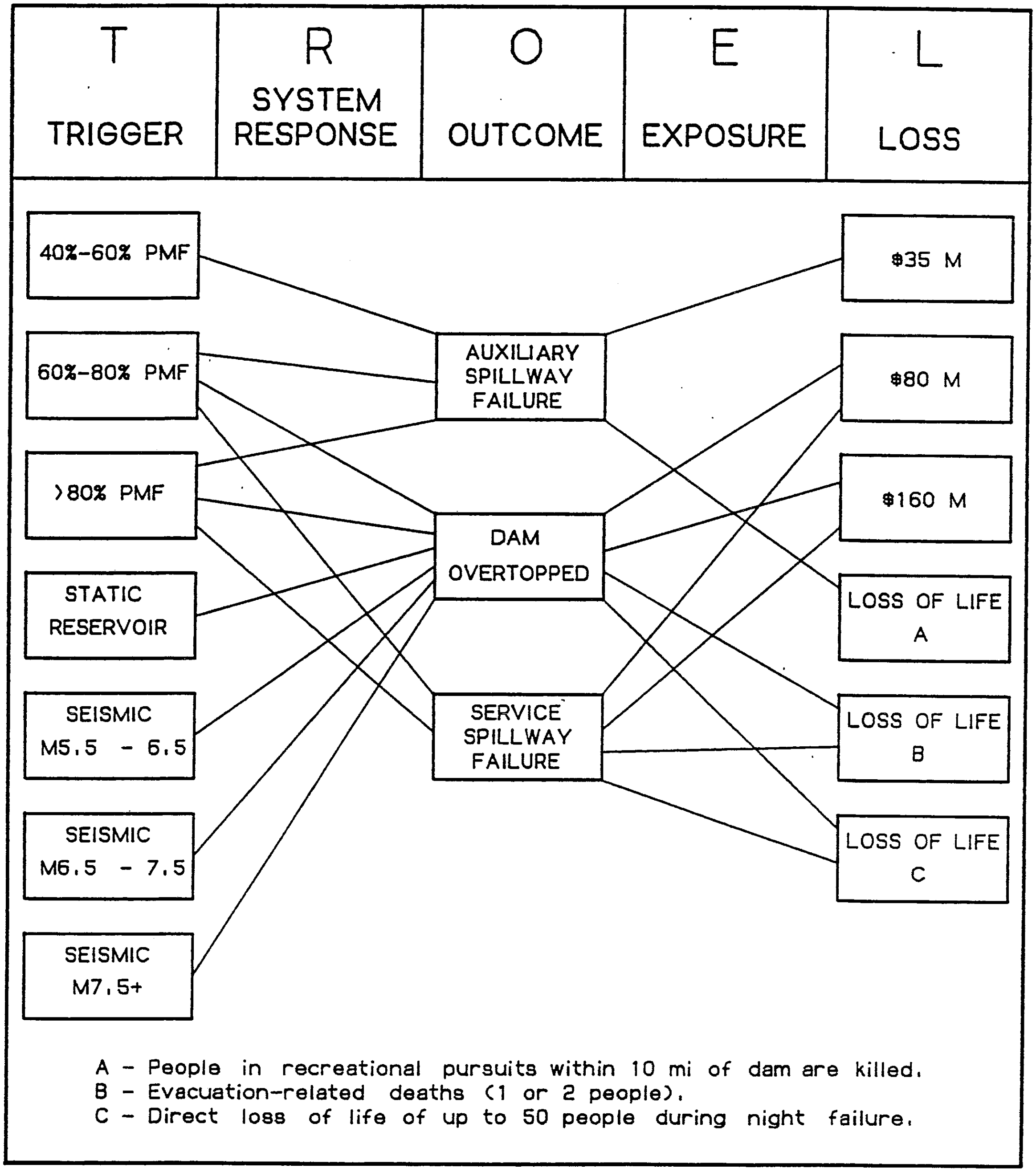
ANALYSIS OF DAM SAFETY BY U.S. BUREAU OF RECLAMATION

The use of risk analysis in Dam Safety work has recently been developed by Utah State University (Bowles et al., 1986) and the U.S. Bureau of Reclamation (Von Thun, 1986). Though no specific dam safety analysis results are currently available, the typical dam problem presented by Von Thun (1986) with some embellishments by the authors can be used as a further demonstration of the risk-based procedure presented in this paper.

A hypothetical earth dam is of moderate size (30 m) and value, and is in a sparsely inhabited rural location. The spillway can safely pass only 40% of the probable maximum flood (PMF) and the stability of the dam under seismic loading has been questioned. Further, the embankment foundation conditions are not well known and seepage has been observed at the abutment. The possibility of failure by piping under static reservoir conditions exists. Figure 5 shows an event diagram showing possible combinations of events leading to a loss. Several types and magnitudes of events are included under the trigger, outcome and loss categories. Though the system response and exposure categories have been itemized in dam safety work by Utah State University (Anderson and Bowles, 1987), the USBR work simplifies the analysis by excluding them. Note that links between some of the events have been eliminated as they are deemed very unlikely. Figure 6 shows the event tree corresponding to the event diagram. A total of 22 linkages are developed in this case study which allow us to assess combinations of flood magnitude, earthquake loading, dam failure modes and levels of consequential damage. Table 3 is a risk calculation table for the 22 linkages.

Though the probability values in Table 3 are hypothetical, they do illustrate some interesting points. First, the failure of a dam from a Magnitude 7.5 or greater earthquake may seem to, the public eye to be one of the highest risks to life and property. But in fact, it can be quite minor compared to the risk due to dam failure from piping. Compare the annual risk costs (ARC) values of \$2,400 for the former versus \$20,000 for the latter. Second, the lower magnitude events such as a 40-60% PMF may pose a higher risk than the higher magnitude events because they are likely to be more frequent.

The risk table is a convenient way to analyze the effects of various mitigative measures. Using the USBR data, Table 4 shows the effects of adding a 1 m parapet wall to the dam to reduce the probability of overtopping and a downstream filter zone to reduce the probability of piping. (Note that the risk of piping has not been completely eliminated because of the uncertain embankment/foundation conditions). Table 4 shows the revised risk calculation table which takes this into account. It can be seen that a reduction in annual risk cost by one third is accomplished by these measures. At the same



A - People in recreational pursuits within 10 mi of dam are killed.
B - Evacuation-related deaths (1 or 2 people).
C - Direct loss of life of up to 50 people during night failure.

Figure 5. Event diagram for USBR hypothetical dam safety case study.

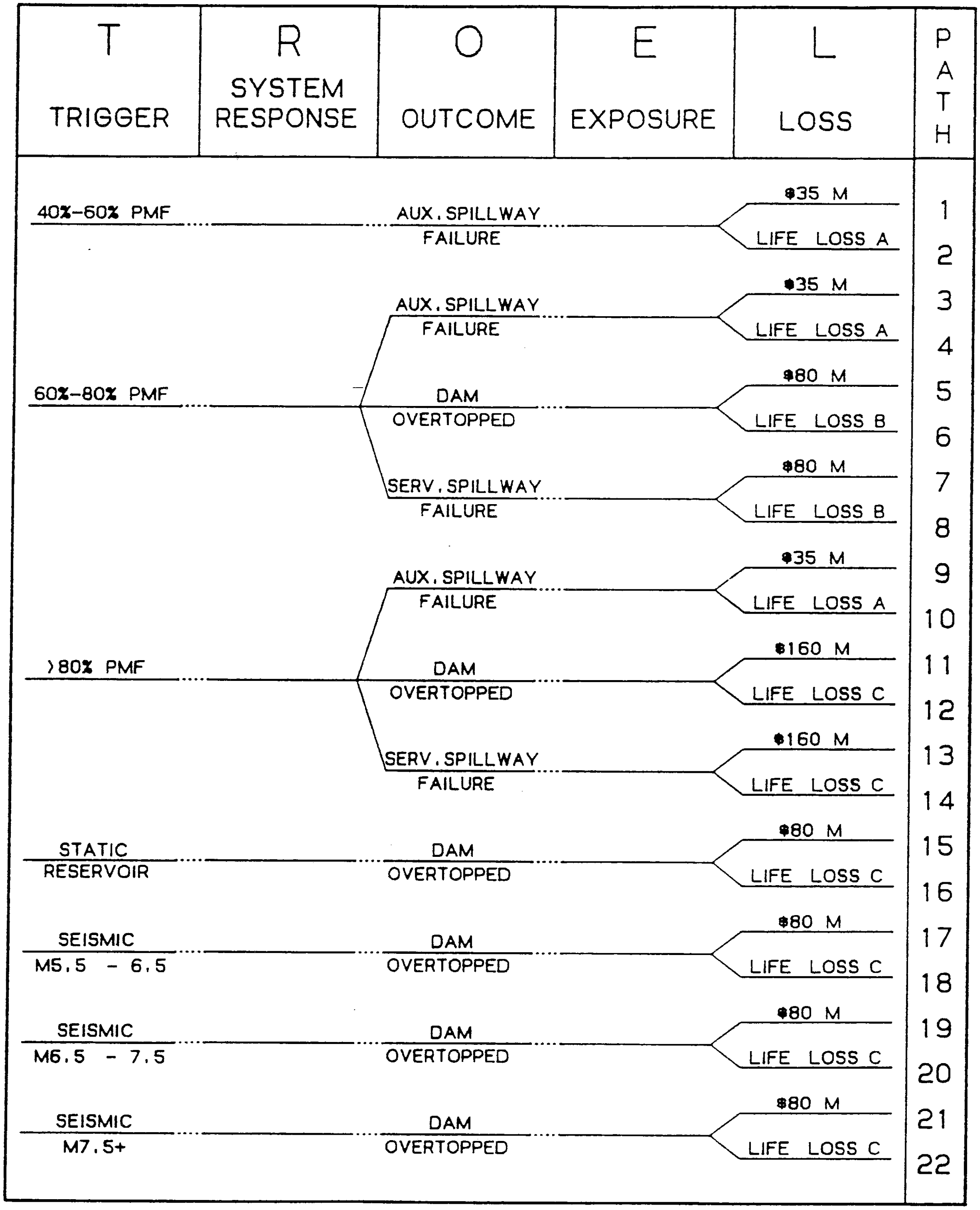


Figure 6. Event tree for USBR hypothetical dam safety case study.

Table 3. Risk calculation table for USBR hypothetical dam safety case study. Calculated probabilities are before mitigation.

LINKAGE NUMBER	P(O)			EX(L¦O)			ARC	PND $(X10^{-3})$
	P(T)	P(O¦T)		P(L¦O)		L		
	P(R)		P(O¦R)	P(E¦O)	EX(L¦E)			
	P(T)	P(R¦T)	P(O¦R)	P(E¦O)	P(L¦E)	L		
1	40%-60% PMF 0.004	AUXILIARY SPILLWAY FAILURE 0.10		COST $35 M			$14,000	
2	40%-60% PMF 0.004	AUXILIARY SPILLWAY FAILURE 0.10		LOSS OF LIFE 1				0.40
3	60%-80% PMF 0.0008	AUXILIARY SPILLWAY FAILURE 0.30		COST $35 M			$8,400	
4	60%-80% PMF 0.0008	AUXILIARY SPILLWAY FAILURE 0.30		LOSS OF LIFE 1				0.24
5	60%-80% PMF 0.0008	DAM OVERTOPPED 0.05		COST $80 M			$3,200	
6	60%-80% PMF 0.0008	DAM OVERTOPPED 0.05		LOSS OF LIFE 2				0.08
7	60%-80% PMF 0.0008	SERVICE SPILLWAY FAILURE 0.05		COST $80 M			$3,200	
8	60%-80% PMF 0.0008	SERVICE SPILLWAY FAILURE 0.05		LOSS OF LIFE 1				0.08
9	> 80% PMF 0.0002	AUXILIARY SPILLWAY FAILURE 0.5		COST $35 M			$3,500	
10	> 80% PMF 0.0002	AUXILIARY SPILLWAY FAILURE 0.5		LOSS OF LIFE 1				0.10
11	> 80% PMF 0.0002	DAM OVERTOPPED 0.2		COST $160 M			$6,400	
12	> 80% PMF 0.0002	DAM OVERTOPPED 0.2		LOSS OF LIFE 50				2.00
13	> 80% PMF 0.0002	SERVICE SPILLWAY FAILURE 0.1		COST $160 M			$3,200	
14	> 80% PMF 0.0002	SERVICE SPILLWAY FAILURE 0.1		LOSS OF LIFE 50				1.00
15	STATIC RESERVOIR 0.5	DAM OVERTOPPED 0.0005		COST $80 M			$20,000	
16	STATIC RESERVOIR 0.5	DAM OVERTOPPED 0.0005		LOSS OF LIFE 50				12.5
17	SEISMIC M5.5 - M6.5 0.01	DAM OVERTOPPED 0.005		COST $80 M			$4,000	
18	SEISMIC M5.5 - M6.5 0.01	DAM OVERTOPPED 0.005		LOSS OF LIFE 50				2.5
19	SEISMIC M6.5 - M7.5 0.001	DAM OVERTOPPED 0.1		COST $80 M			$8,000	
20	SEISMIC M6.5 - M7.5 0.001	DAM OVERTOPPED 0.1		LOSS OF LIFE 50				5.0
21	SEISMIC M7.5+ 0.0001	DAM OVERTOPPED 0.3		COST $80 M			$2,400	
22	SEISMIC M7.5+ 0.0001	DAM OVERTOPPED 0.3		LOSS OF LIFE 50				1.5

ANNUAL RISK COST = $76,300

PROBABLE NUMBER OF DEATHS PER ANNUM = 25.4 X 10^{-3}

Table 4. Risk calculation table for USBR hypothetical dam safety case study after the addition of a 1 m parapet wall and a filter zone on the downstream face.

LINKAGE NUMBER	P(O)			EX(L¦O)			ARC	PND (X10^{-3})
	P(T)	P(O¦T)		P(L¦O)		L		
	P(R)		P(O¦R)	P(E¦O)	EX(L¦E)			
	P(T)	P(R¦T)	P(O¦R)	P(E¦O)	P(L¦E)	L		
1	40%-60% PMF 0.004	AUXILIARY SPILLWAY FAILURE 0.10		COST $35 M			$14,000	
2	40%-60% PMF 0.004	AUXILIARY SPILLWAY FAILURE 0.10		LOSS OF LIFE 1				0.40
3	60%-80% PMF 0.0008	AUXILIARY SPILLWAY FAILURE 0.30		COST $35 M			$8,400	
4	60%-80% PMF 0.0008	AUXILIARY SPILLWAY FAILURE 0.30		LOSS OF LIFE 1				0.24
5	60%-80% PMF 0.0008	DAM OVERTOPPED 0		COST $80 M			0	
6	60%-80% PMF 0.0008	DAM OVERTOPPED 0		LOSS OF LIFE 2				0
7	60%-80% PMF 0.0008	SERVICE SPILLWAY FAILURE 0.05		COST $80 M			$3,200	
8	60%-80% PMF 0.0008	SERVICE SPILLWAY FAILURE 0.05		LOSS OF LIFE 1				0.08
9	> 80% PMF 0.0002	AUXILIARY SPILLWAY FAILURE 0.5		COST $35 M			$3,500	
10	> 80% PMF 0.0002	AUXILIARY SPILLWAY FAILURE 0.5		LOSS OF LIFE 1				0.10
11	> 80% PMF 0.0002	DAM OVERTOPPED 0		COST $160 M			0	
12	> 80% PMF 0.0002	DAM OVERTOPPED 0		LOSS OF LIFE 50				0
13	> 80% PMF 0.0002	SERVICE SPILLWAY FAILURE 0.1		COST $160 M			$3,200	
14	> 80% PMF 0.0002	SERVICE SPILLWAY FAILURE 0.1		LOSS OF LIFE 50				1.00
15	STATIC RESERVOIR 0.5	DAM OVERTOPPED 0.0003		COST $80 M			$12,000	
16	STATIC RESERVOIR 0.5	DAM OVERTOPPED 0.0003		LOSS OF LIFE 50				7.5
17	SEISMIC M5.5 - M6.5 0.01	DAM OVERTOPPED 0		COST $80 M			0	
18	SEISMIC M5.5 - M6.5 0.01	DAM OVERTOPPED 0		LOSS OF LIFE 50				0
19	SEISMIC M6.5 - M7.5 0.001	DAM OVERTOPPED 0.06		COST $80 M			$4,800	
20	SEISMIC M6.5 - M7.5 0.001	DAM OVERTOPPED 0.06		LOSS OF LIFE 50				3.0
21	SEISMIC M7.5+ 0.0001	DAM OVERTOPPED 0.2		COST $80 M			$1,600	
22	SEISMIC M7.5+ 0.0001	DAM OVERTOPPED 0.2		LOSS OF LIFE 50				1.0

ANNUAL RISK COST = $50,700

PROBABLE NUMBER OF DEATHS PER ANNUM = 13.3 X 10^{-3}

time, the annual probable number of deaths (PND) is approximately halved, from 0.0254 to 0.0133. These benefits of reduced risk can thus be balanced against the costs of adding the parapet wall and filter to determine whether it is cost effective.

The exposure of a select individual to the risk of dam failure is not considered in this case history for reasons discussed in the following section.

YARD-STICKS OF ACCEPTABLE RISK

We all take risks and from the standpoint of the individual risk-taker, society dearly establishes levels of risk which it finds acceptable. A selection of these risk levels is given in Table 5.

ACTIVITY	[1]PROBABILITY OF DEATH/YR
VOLUNTARY INDIVIDUAL RISKS:	
Commercial Diving	1:350
Air Travel (crew)	1:1000
Agriculture	1:2000
[2]Car Travel (B.C. 1984)	1:3500
Motorcycle Racing	1:5000
Construction	1:1500 - 1:6000
All Industry (U.S.)	1:7000
Air Travel (passenger)	1:9000
INVOLUNTARY INDIVIDUAL RISKS:	
Fire	$1:50 \times 10^3$
Drowning	$1:100 \times 10^3$
Natural Hazards (Norway)	$1:350 \times 10^3$
Lightning	$1:5000 \times 10^3$
Structural Failure	$1:10{,}000 \times 10^3$

[1] Relative to the population employed in, or exposed to, the activity

[2] For an individual travelling 10,000 km/yr.

Sources: Ministry of Transportation and Highways (1984); Kinchin (1978); Rodin (1978); Cohen et al. (1978); Hestnes et al. (1980).

It is apparent that an acceptable level depends on:

- the individual and the occupation or activity he is willing to pursue.

- whether the risk is voluntarily assumed or one that is imposed (involuntary).

- present values (which can change with time).

Table 5 indicates that society is willing to accept voluntary risks which are roughly 1000 times greater than involuntary risks. However, the individual member of society rarely has any control over the siting and operation of large civil works or over such planning functions as zoning of residential lands with respect to natural hazards. Under these conditions, one would expect any imposed risks not to exceed those corresponding to the involuntary level in Table 5 which appears to be of the order of 10^{-6} (PDI). Thus, referring to the Silverhope rock hazard case history (Table 2), it is evident that although approval by a public authority of housing in the talus zone is obviously unacceptable, a good case can be presented for subdivision of lands beyond the rockfall shadow zone.

Such a comparison of imposed risks with those already assumed by the individual avoids attempting to place a value on life and the emotional and political arguments associated with such a task.

With respect to projects that have the capability of catastrophic failure (involving a significant number of fatalities at one time), different yard-sticks must be established. We must bear in mind that no argument based on acceptable individual levels of risk would be successful in the emotional aftermath of such a disaster. The second case history concerning the hypothetical dam falls into this category and it is for this reason the individual PDI is not considered. Whether the dam has been designed and constructed in accordance with established engineering procedures for such structures, whether the potential hazard causing the failure could have been recognized, and whether the design was reviewed and by whom would be of much greater relevance under such circumstances.

The purpose of risk assessment of dams and other structures capable of catastrophic failure lies with design and maintenance (upgrading). This approach can be very helpful in:

- Establishing and prioritizing the need for upgrading a dam out of several dams. Historical records of dam failure (Tarvil, 1986) have shown that large modern earth fill dams have a probability of failure of approximately 1 x 10^{-4} per dam per year, and significantly the probability of failure after the first 5 years of operation drops to 5 x 10^{-5} per dam per year. Using this yardstick, the hypothetical dam, as portrayed in the first two columns P(O) of Table 3, is shown to be borderline but with no outstanding weaknesses. Consequently, work on this dam might be delayed in favour of one in greater need.

- Establishing the extent to which risk to life and property is reduced by various possible mitigative measures, and thus determining the cost effectiveness of these measures.
- From a series of possible events which would threaten the dam, determining the combination of conditions which imposes the greatest risk. In effect this leads to a better understanding of the vulnerability of the dam.

CLOSING REMARKS

The most common criticism of procedures for risk assessment as applied to natural hazards and civil structures centers on the difficulty of selecting probabilities for each of the events in a linkage. However, increasingly we find the approach to be a useful tool in performing sensitivity analyses. As often as not, approximation of probabilities based on good engineering judgment is all that is necessary.

At the very least, this procedure leads to an organized and uniform approach to assessing the vulnerability of our work.

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APPENDIX

Total risk is given by the equations as derived from the theorem of total probabilities (Mood et al., 1974, p.37):

$$\mathrm{ARC} = \sum_{i=1}^{n} \sum_{j=1}^{o} \sum_{k=1}^{p} \sum_{l=1}^{q} \sum_{m=1}^{r} P(T_i)\ P(R_j|T_i)\ P(O_k|R_j)\ P(E_l|O_k)\ P(L\$_m|E_l)\ L\$_m$$

for annual risk cost

$$\mathrm{PND} = \sum_{i=1}^{n} \sum_{j=1}^{o} \sum_{k=1}^{p} \sum_{l=1}^{q} \sum_{m=1}^{r} P(T_i)\ P(R_j|T_i)\ P(O_k|R_j)\ P(E_l|O_k)\ P(L^{*}_m|E_l)\ L^{*}_m$$

for probable number of deaths per annum and

$$\mathrm{PDI} = \sum_{i=1}^{n} \sum_{j=1}^{o} \sum_{k=1}^{p} \sum_{l=1}^{q} \sum_{m=1}^{r} P(T_i)\ P(R_j|T_i)\ P(O_k|R_j)\ P(E_l|O_k)\ P(L^{I}_m|E_l)$$

for the annual probability of an individual death. The subscripts i though m represent the number of types and magnitudes of each category of event analyzed. The use of all subscripts in the equations results in the linkage of all possible combinations of events in an event diagram such as the one shown in Figure 1. The analyst has the option of not considering some of the linkages if it is deemed that the probabilities of them happening are sufficiently low.