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QUANTITATIVE RISK ANALYSIS FOR A CUT SLOPE

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ABSTRACT

Landslides may result in adverse consequences to the population including injuries and fatalities. Estimating the factor of safety of a slope without considering failure consequences falls short of addressing the totality of adequate slope design. Quantitative risk analysis (QRA) combining hazard frequency and failure consequences is a more rational basis for judging the acceptability of a slope. An example site-specific QRA study for a cut slope in Hong Kong is undertaken using an event tree analysis. The assessment focuses on estimating the risk of loss of life for the residents of a housing block located at the foot of the slope as a result of slope failure. The study addresses the temporal and spatial distribution of the population at risk, the development of signs of slope distress, the efficiency of warning and emergency response measures, the travel distance of the slide debris and the amount of protection offered by the building.

1. INTRODUCTION

Landslides may result in adverse consequences to the population including injuries, fatalities, economic losses and environmental damage. Estimating the factor of safety, or the failure probability, of a slope without considering failure consequences falls short of addressing the totality of adequate slope design. Two slopes with the same levels of safety may be treated very differently depending on the failure consequences. By combining hazard frequency and failure consequences, quantitative risk analysis (QRA) provides a rational basis for judging the acceptability of a slope. This paper illustrates an example QRA study for a cut slope in Hong Kong.

2. THE SHEK KIP MEI SLOPE FAILURE

On August 25, 1999 the cut slope located 5m behind housing Block No. 36 of the Shek Kip Mei Estate in Hong Kong failed. Failure occurred on the last day of an intense 4-day rainstorm. The height of the slope was about 21 m. The slope configuration comprised 5 batters each dipping at an angle of 55 degrees to the horizontal (0.7h:1v) with 1-2 m wide berms in-between. The displaced mass, which remained largely intact, was approximately 37 m wide and had an estimated volume of 2500 m^3. The mobility of the displaced mass was limited, in the order of 1 m, and most of the material remained on the slope. Nonetheless, the detachment and collapse of localized areas on the slope resulted in relatively mobile material. Prior to failure, numerous signs of slope distress were observed which prompted the Geotechnical Engineering Office of Hong Kong to order the evacuation of Block 36.

A comprehensive investigation of the failure was sponsored by the Geotechnical Engineering Office of Hong Kong (FMSW, 2000). Based on the published results of the failure investigation, El-Ramly (2001) re-designed the slope (hypothetically) to a flatter inclination deemed stable. Maintaining the same configuration of the failed slope, the modified design has an overall slope angle of 31.2 degrees (1.65h:1v) as shown in Figure 1. The minimum factor of safety of the re-designed slope is 1.45, and the probability of unsatisfactory performance (probability of factor of safety being less than one) is 2.09×10^{-3}. In the following sections, an event tree analysis is undertaken to demonstrate the implementation of a site-specific QRA study for the re-designed slope. The assessment is focused on estimating the risk of loss of life for the residents of Block 36 at the foot of the slope.

3. FRAMEWORK OF QRA

Quantitative risk analysis comprises several components namely; hazard identification, hazard analysis, consequences analysis, and the integration of the results of hazard and consequences analyses to yield measures of risk. First, all potential credible hazards that could result in undesirable consequences are identified. Three hazards are addressed in this assessment. All are sliding shear failures but of different scales, as summarized in Table 1. In a more comprehensive study, other failure modes, such as liquefaction and washout, should also be considered. Second, the probability of occurrence of each hazard is estimated (El-Ramly, 2001). The investigation of the slide (FMSW, 2000) suggested that the slide was triggered by the rainstorm of August 21-25 1999, which had an estimated return period of 31 years. Hence, the annual probability of each hazard is the product of the probability of unsatisfactory performance and the annual frequency of the triggering rainstorm (3.2×10^{-2}), as summarized in Table 1.

The potential consequences of each hazard are evaluated. For each of the three identified hazards, an event tree comprising a number of possible scenarios relevant to the failure of slope is developed and the frequency of each scenario is estimated. The event trees address the temporal variability of the elements at risk

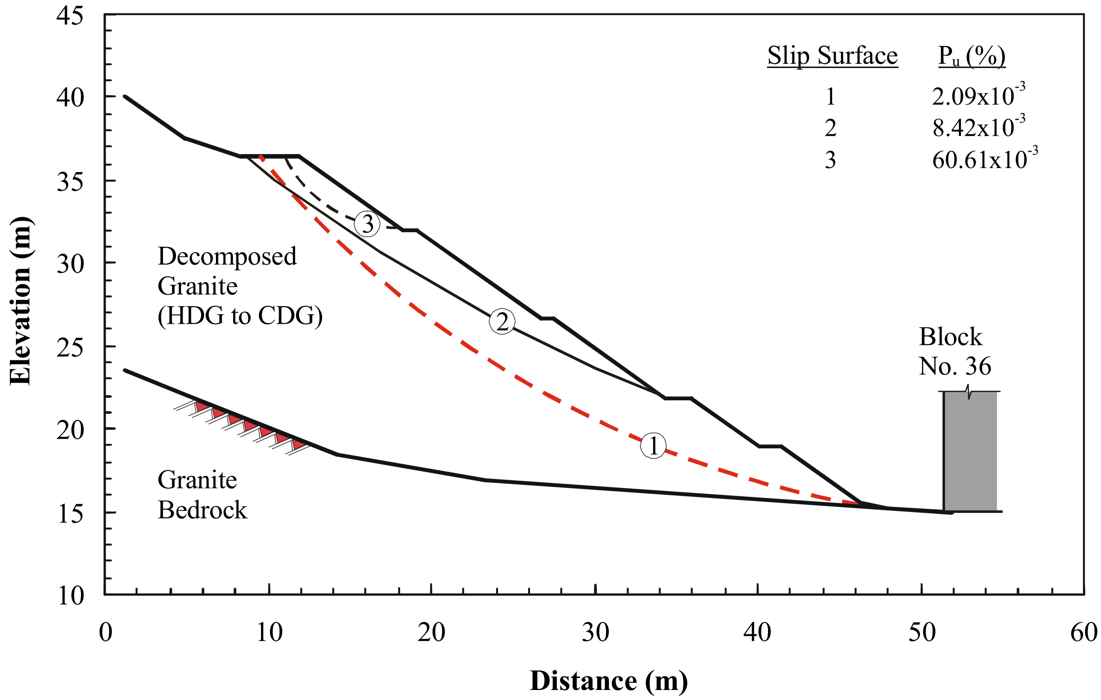

Figure 1. Sliding failure hazards considered in QRA study.

Table 1. Summary of hazards addressed in QRA.

Hazard No.	Description	Failure Height (m)	Estimated Slide Volume[a] (m^3)	Slip Surface No. (Figure 1)	Probability of Unsatisfactory Performance [b]	Hazard Probability (per year)
1	Deep-seated failure involving total slope height	20.8	2500-5000	1	2.09×10^{-3}	0.67×10^{-4}
2	Shallow failure involving 70% of slope height	14.6	300-600	2	8.42×10^{-3}	2.72×10^{-4}
3	Shallow localized failure	4.5	25-50	3	60.61×10^{-3}	1.96×10^{-3}

[a] assuming that the width of the slide is 1-2 times its height
[b] from El-Ramly (2001)

(residents of Block 36), the development of signs of slope distress, the efficiency of warning and emergency response measures, the travel distance of the slide debris and the amount of protection offered by the building. The likely consequence of each event tree scenario is obtained based on estimates of the number and vulnerability of the people at risk. It should be noted that the data available for this type of analyses are seldom complete and the subjective assessment of some of the inputs to QRA is inevitable.

Finally, the frequencies of occurrence of event tree scenarios are combined with the estimated number of fatalities for all the identified hazards to give a measure of risk. The total estimated figure represents the societal risk of loss of life for the population at risk as a result of slope failure. The results are presented in two forms; the potential loss of life (PLL), and the F-N curve (a plot of the cumulative frequency of N or more fatalities, F, versus the number of fatalities, N, on a log-log scale).

4. EVENT TREE ANALYSIS

An event tree analysis is a structured process used to address a number of possible consequences following an initiating event, such as slope failure. Starting with the initiating event and using inductive reasoning, the structure of the tree identifies all possible scenarios and estimates the probability of the outcome of each scenario. For any of the outcomes to occur, a sequence of subsequent events represented by a certain path in the event tree must occur. The probabilities of the tree branches are, often, estimated judgmentally. Historical data and analytical/empirical models are commonly used to guide the assessment. The probability of occurrence of a specific outcome is the product of all the conditional probabilities associated with the tree branches leading to this particular outcome.

Event tree analysis is, probably, the most common technique used in risk analyses. By breaking down the problem into a number of simpler scenarios, event trees greatly facilitate the exercising of transparent and consistent judgment. Wong et al. (1997) pointed out that subjective estimates are naturally open to debate. The division of the problem into a number of elementary components reduces the scope of debate, as all the assumptions made may not be in dispute. It also facilitates more effective communication and discussion of the assessors' judgments.

The event tree used for the analysis of Hazard No. 1 is illustrated in Figure A.1 in Appendix A, and a description of the structure of the tree is presented in the following sections. The analysis is performed using an Excel spreadsheet. Not all the information needed for the analysis was available and some assumptions were made, such as number of residents in Block 36 and the type of the building.

4.1 Time of Failure

The first branch of the event tree addresses the time of occurrence of the slide namely; day or night. The probabilities of the slide occurring during the day or night are intuitively similar and equal to 0.5. However, the consequences of failure could be markedly different. Given that signs of slope distress occur, the effectiveness of warning measures and the efficiency of emergency response (e.g., evacuation of the building) are largely reduced during the night compared to the daytime. More importantly, the number of building occupants (i.e., elements at risk) varies significantly between the day and night.

4.2 Signs of Slope Distress

The second branch of the tree considers the development of signs of slope distress. The failure of the original Shek Kip Mei slope was preceded by numerous signs of slope distress. It is assumed that the same scenario is likely to happen, should the modified slope being analyzed also fail. The development of signs of slope distress is judgmentally assigned a probability of occurrence of 0.85.

4.3 Warning and Response Measures

Next, the efficiency of warning and emergency response measures is addressed. The probability of effective warning and evacuation measures can only be assessed judgmentally. Should the slide occur during the daytime, the probability of efficient warning and response measures is assumed 0.80. If the slope fails at night, the probability is reduced to 0.5. In the absence of signs of slope distress prior to failure, i.e. sudden collapse of the slope, the probability of an effective warning and emergency response is considered zero

4.4 Travel Distance of Displaced Material

The following tree branch considers the travel distance of the slide debris. The debris travel distance defines the extent of the area affected by the slide and is one of the most important factors in assessing the failure consequences. The travel of the debris is governed by factors such as slope height and gradient, type of soil forming the slope, failure mode, scale of failure, degree of disintegration of the failed mass during movement, amount of water in the debris and the gradient of the downslope area. Given the complexities in quantifying these factors, predicting the debris travel distance is extremely difficult. Using the large database of slope failure incidents in Hong Kong, Wong and Ho (1996) and Wong et al. (1997) established empirical correlations between the landslide volume and the "travel angle" (the inclination of the line joining the slope crest and the tip of the debris, Figure 2).

The database of rain-induced sliding failures gathered by Wong et al. (1997) is used in this study to assess the likely ranges of the debris travel angle for the three hazards considered. For each hazard, three potential travel angles are selected to account for the uncertainty in travel distance predictions. The probability of each travel angle is evaluated judgmentally based on the database of Wong et al. (1997) and the field observations of debris mobility at Shek Kip Mei slide. For Hazard No. 1, a travel angle in the range of 25-30 degrees is considered reasonable. The corresponding outward movements at the toe of the slope are in the range of 10m to 2m, respectively, which are consistent with the observed low mobility of the failed mass. Because of the large volume of failure, there is a small chance that the mobility of the debris may increase by the break up of the failed material during movement. A travel angle of 20 degrees is also considered. Three travel angles, 20, 25 and 30 degrees, are taken into account in the event tree with respective probabilities of 0.05, 0.55 and 0.40. Figure 2 shows the limit of debris travel for each scenario.

4.5 Damage to Block 36 at Impact by Slide Debris

The ultimate outcome of the slope failure is the damage to Block 36. Three possibilities are considered; the building collapses under the impact of the debris, the building does not collapse but the debris enters the ground floor, and the building withstands the impact and suffers no damage. The likelihood (or probability) of each scenario is a function of debris travel angle, scale of failure, impact energy and building structure. Obviously, the extent of damage affects the probability of death and the number of people at risk.

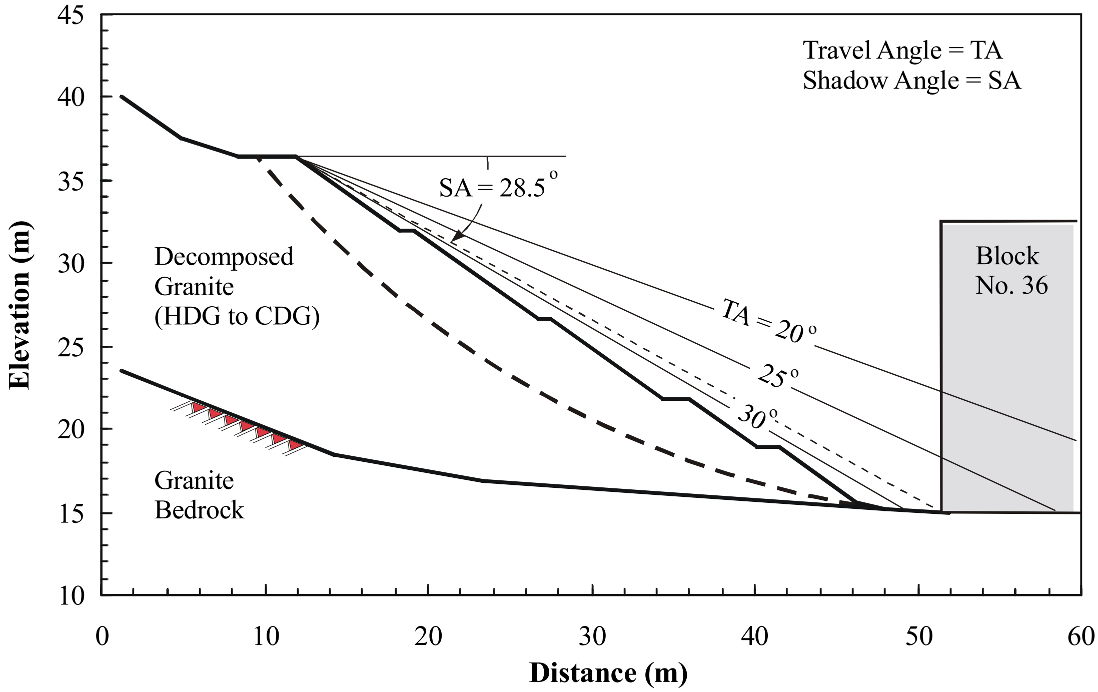

Figure 2 Limits of landslide debris travel for Hazard No. 1 relative to the location of Block 36

The proximity of a facility to the slide could be expressed in terms of the "shadow angle" (Wong et al., 1997). It is defined as the inclination of the line joining the crest of the slope and the toe of the facility, as shown in Figure 2. For Block 36, the shadow angle is about 28.5 degrees. Comparing the shadow angle with the presumed travel angles, Figure 2, suggests that damage to Block 36 can only be attained as a result of an impact by debris with a travel angle less than 30 degrees. No information is available about the structure of Block 36. However, it is judged that the building is likely to collapse under the impact of a large volume of highly mobile debris (travel angle of 20 degrees). Slides with debris travel angles greater than 30 degrees are assumed to have no effect on the building. The probabilities of the three postulated scenarios are evaluated judgmentally based on the debris travel angle, the shadow angle and the size of the slide. The proposed probabilities for Hazard No. 1 are indicated on the branches of the event tree in Figure A.1 in Appendix A.

4.6 Probabilities of Event Tree Outcomes

The event tree established for Hazard No. 1 identifies forty possible scenarios as shown in Figure A.1 in Appendix A. Scenario No. 22, for example, is the collapse of Block 36 under the impact of mobile debris resulting from the failure of the slope at night. The failure was preceded by signs of slope distress, but the efficiency of the emergency response measures was poor. The probability of occurrence of each scenario is the product of the probabilities of all tree branches leading to this particular scenario, as indicated in Figure A.1.

5. CONSEQUENCE ASSESSMENT

5.1 Elements at Risk

The first step in assessing failure consequences is to evaluate the number of people endangered by the slide. That number largely depends on the time of failure (i.e., day or night) as well as the extent of damage to the building. For example, if the building collapses, all the residents present at the time of failure are at risk. On the other hand, if the building did not collapse but the debris enters the building, only those residents on the ground floor are at risk. In the absence of any information regarding the number of residents in Block 36, the assessment is based on an assumed population density of 0.05 person/m^2 per floor (the building comprised 6 floors). This figure was used by ERM (1996) in similar studies in Hong Kong. Only 25% of the residents are assumed to be present during the daytime. The number of people at risk for each event tree scenario is estimated and presented next to the corresponding tree branch, as shown in Figure A.1 in Appendix A.

5.2 Probability of Death

Having estimated the number of people at risk, the next step is to estimate their vulnerability, or the probability of death. It is governed primarily by the extent of damage to the building and the volume of landslide debris. There are no technical means, yet, to estimate the probability of death and it is solely based on judgment. ERM (1999), however, indicated that past incidents of total building collapse in Hong Kong involved a high mortality rate of possibly 90% or higher of building occupants. DNV (1996) exercised their judgement in estimating the probability of death for a number of event tree scenarios describing the impact of landslide debris on a wide range of facilities (road, footpath, building) situated at the toe of the slope. Likewise, the probabilities of death in this assessment are estimated judgmentally. Reference is made, however, to the DNV (1996) study. For Hazard No. 1, the probability of death is assumed 1.0 for the total collapse of the building; 0.6 in the event of the slide debris entering the ground floor; and 0.0 for no interaction between the building and the slide debris. The probability figures are indicated next to the event tree braches in Figure A.1.

6. RISK ESTIMATION

The risk of loss of life from a sliding failure of the Shek Kip Mei slope is estimated by integrating the outcomes of the event tree analysis and the consequences assessment. The output is an estimate of the frequency of occurrence of each event tree scenario, f, and the corresponding expected number of fatalities, N. For example, Scenario No. 15 in Figure A.1 (collapse of Block 36 following an impact by a moderately mobile debris resulting from a sudden large slope failure during the daytime) has a frequency of occurrence of 6.94×10^{-7} per year and an expected number of fatalities of 40.5 persons. The number of fatalities is obtained by multiplying the number of people at risk by the probability of death. Since sliding failure triggered by rainfall is the only failure mechanism considered, the estimated risk figures should be regarded as a lower bound to the total risk.

The computed risk is the societal risk of loss of life to the residents of Block 36 and is presented in two forms; the potential loss of life (PLL) and the F-N curve. The potential loss of life is the average annual fatality rate associated with the failure of Shek Kip Mei slope. It is equal to the summation of the products of the frequency of occurrence and the number of fatalities for all scenarios for all hazards. For the investigated slope, the PLL is estimated to be 8.08×10^{-4} per year. A break down of this figure is illustrated in Table 2. The risk of loss of life as a result of a significant slope failure (Hazard No. 1) represents 95% of the total risk, whereas the risk associated with a minor failure (Hazard No. 3) is almost zero. Also, the risks associated with the scenarios involving the collapse of Block 36 during the night is about 5.71×10^{-4} per year; nearly 71% of the total PLL.

The F-N curve is a plot of the frequency of occurrence of N or more fatalities (i.e., cumulative frequency), F, versus the number of fatalities, N. It is computed by summing all the frequencies corresponding to event tree scenarios with a number of fatalities equal to or more than N for all the identified hazards. Figure 3 shows the F-N curve of the total risk due to Hazards 1, 2 and 3.

Table 2 Annual potential loss of life (PLL) as a result of a sliding failure of the Slope

Hazard	Slide	Potential Loss of Life (per year)		
		For All Event tree Scenarios	% of Total	Due to Building Collapse at Night
1	2500-5000	7.67×10^{-4}	94.9	5.49×10^{-4}
2	300-600	4.08×10^{-5}	5.1	2.21×10^{-5}
3	25-50	0.00	0.0	0.00
Total PLL =		8.08×10^{-4}		5.71×10^{-4}

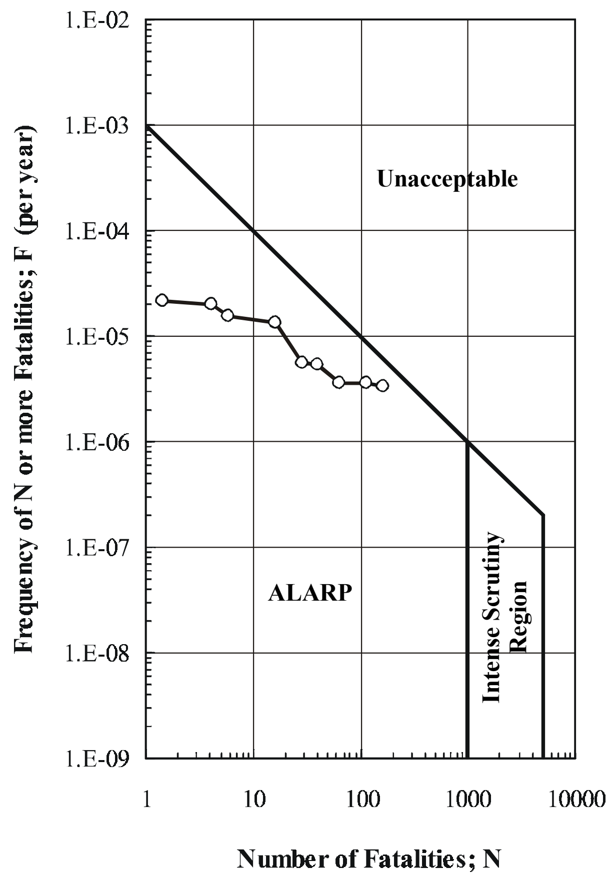

Figure 3 Calculated F-N curve for sliding failure of the investigated slope, and the ERM (1999) risk acceptance criteria

7. DISCUSSION AND CONCLUSION

The F-N curves for Hazard No. 1 and the total risk (Figure 3) are very similar; in fact they could not be plotted on the same graph because they almost coincide with each other. This indicates that the majority of the total risk is attributed to Hazard No. 1. This is also evident from examining the estimated values of the potential loss of life. The PLL of Hazard No. 1 constitutes 95% of the total value, whereas the contributions of Hazards 2 and 3 are 5% and

0%, respectively. This makes an interesting point. The probability of unsatisfactory performance of Hazard No. 3 is significantly higher than that of Hazard No. 1, as shown in Table 1. Yet, the risk associated with Hazard No. 1 is significantly higher. An adequate slope design should not, thus, be governed by the high probability of unsatisfactory performance of localized failures. A more efficient design might consider stabilizing minor instabilities individually. In Hong Kong, soil nailing has proved to be very successful and is widely used to deal with local unstable sections.

The consequence assessment is dominated by one scenario: the collapse of Block 36 during the night, which contributes almost 71% of the total PLL (Table 2). Despite its small frequency of occurrence (3.58×10^{-6} per year; a return period of 279,000 years), the expected high level of fatalities has largely magnified the contribution of such a rare scenario to the total risk.

A rigorous assessment of the acceptability of the estimated risk is beyond the scope of this study. However, some general comments ought to be made. The interim risk criteria for landslides and boulder falls from natural terrain proposed by ERM (1999) and Reeves et al. (1999) is compared to the F-N curve of the total risk as shown in Figure 3. The F-N curve falls within the ALARP (as low as reasonably practicable) region. This means that the risk level is tolerable; however, practical risk mitigation measures need to be considered and evaluated in a cost-benefit analysis. If such measures are proved to be cost effective, they should be implemented.

As discussed earlier, 95% of the risk is attributed to a large slope failure whose probability of unsatisfactory performance is estimated to be 2.09×10^{-3}. This probability value is comparable to the estimated probability of unsatisfactory performance of a tailings dyke performing satisfactorily (El-Ramly et al., 2003). In other words, the slope is reasonably safe from a technical point of view. On the other hand, the consequences of such a large failure are significant, as illustrated in Table 2 and Figure A.1. As such, the risk mitigation alternatives are more cost effective if they aim at reducing the failure consequences rather than lowering the already small probability of unsatisfactory performance. Unfortunately, with the size of failure and the proximity of Block 36 to the slope, there may not be many practical options available.

Some comments on the risk acceptance criteria presented in Figure 3 should be made. First, the ERM (1999) and Reeves et al. (1999) criteria in Figure 3 are for the total risk from all credible hazards, whereas the calculated total F-N curve in this study refers to sliding failures only. Second, the authors of these criteria emphasized that they were untried and should be regarded as guidelines only. Third, the criteria are developed for landslides from natural terrain and not for artificial slopes. An acceptance criterion for artificial slopes, such as the cut at Shek Kip Mei, would be more stringent. ERM (1999) noted, however, that because of the high incidence of landslides in Hong Kong, the public may not perceive much difference between a landslide from natural terrain and the failure of an artificial slope.

Given the above considerations, the risk evaluation presented in this study does not reflect a complete picture of the risk level of the Shek Kip Mei slope. Rather, it is intended to be an illustration of the concepts and the insights gained through a QRA study

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APPENDIX A

Figure A.1. Event tree for the risk analysis of Hazard No. 1

SHEK KIP MEI SLOPE - RISK ANALYSIS

Hazard No. 1 : Deep-Seated Failure Involving Total Height of Slope

Failure Height = 20.8m, Estimated Volume = 2500-5000 m^3

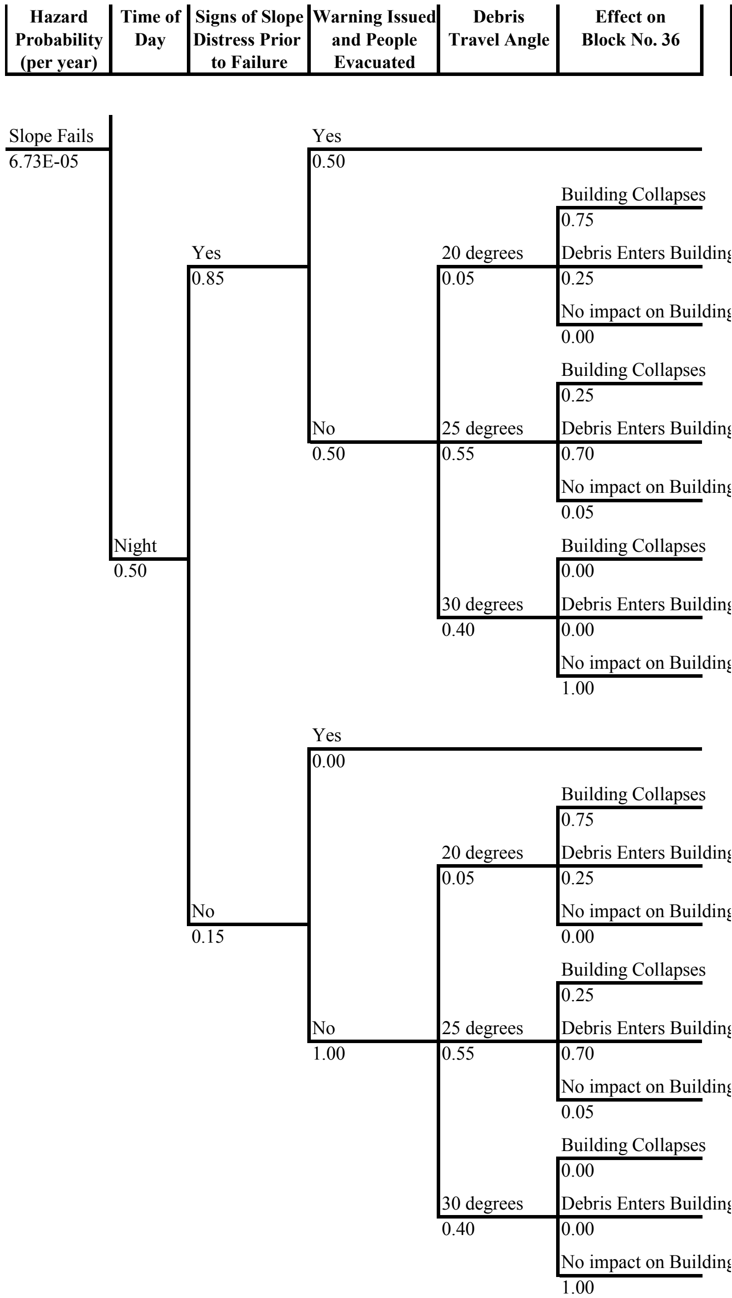
Hazard Probability (per year)	Time of Day	Signs of Slope Distress Prior to Failure	Warning Issued and People Evacuated	Debris Travel Angle	Effect on Block No. 36	Scenario No.	Scenario Frequency (per year)	Number of people at Risk	Probability of Death	Number of Fatalities (N)	Potential Loss of Life (per year)
			Yes 0.80			1	2.29E-05	0.0	0.0	0.00	0.00E+00
					Building Collapses 0.75	2	2.15E-07	40.5	1.0	40.50	8.69E-06
		Yes 0.85		20 degrees 0.05	Debris Enters Building 0.25	3	7.15E-08	6.8	0.6	4.05	2.90E-07
					No impact on Building 0.00	4	0.00E+00	0.0	0.0	0.00	0.00E+00
					Building Collapses 0.25	5	7.87E-07	40.5	1.0	40.50	3.19E-05
			No 0.20	25 degrees 0.55	Debris Enters Building 0.70	6	2.20E-06	6.8	0.6	4.05	8.92E-06
					No impact on Building 0.05	7	1.57E-07	0.0	0.0	0.00	0.00E+00
	Day 0.50				Building Collapses 0.00	8	0.00E+00	40.5	1.0	40.50	0.00E+00
				30 degrees 0.40	Debris Enters Building 0.00	9	0.00E+00	6.8	0.6	4.05	0.00E+00
					No impact on Building 1.00	10	2.29E-06	0.0	0.0	0.00	0.00E+00
			Yes 0.00			11	0.00E+00	0.0	0.0	0.00	0.00E+00
					Building Collapses 0.75	12	1.89E-07	40.5	1.0	40.50	7.67E-06
				20 degrees 0.05	Debris Enters Building 0.25	13	6.31E-08	6.8	0.6	4.05	2.56E-07
		No 0.15			No impact on Building 0.00	14	0.00E+00	0.0	0.0	0.00	0.00E+00
					Building Collapses 0.25	15	6.94E-07	40.5	1.0	40.50	2.81E-05
			No 1.00	25 degrees 0.55	Debris Enters Building 0.70	16	1.94E-06	6.8	0.6	4.05	7.87E-06
					No impact on Building 0.05	17	1.39E-07	0.0	0.0	0.00	0.00E+00
Slope Fails 6.73E-05					Building Collapses 0.00	18	0.00E+00	40.5	1.0	40.50	0.00E+00
				30 degrees 0.40	Debris Enters Building 0.00	19	0.00E+00	6.8	0.6	4.05	0.00E+00
					No impact on Building 1.00	20	2.02E-06	0.0	0.0	0.00	0.00E+00

Figure A.1. Event tree for the risk analysis of Hazard No. 1 (cont'd)

SHEK KIP MEI SLOPE - RISK ANALYSIS

Hazard No. 1 : Deep-Seated Failure Involving Total Height of Slope

Failure Height = 20.8m, Estimated Volume = 2500-5000 m^3



Scenario No.	Scenario Frequency (per year)	Number of people at Risk	Probability of Death	Number of Fatalities (N)	Potential Loss of Life (per year)
21	1.43E-05	0.0	0.0	0.00	0.00E+00
22	5.36E-07	162.0	1.0	162.00	8.69E-05
23	1.79E-07	27.0	0.6	16.20	2.90E-06
24	0.00E+00	0.0	0.0	0.00	0.00E+00
25	1.97E-06	162.0	1.0	162.00	3.19E-04
26	5.51E-06	27.0	0.6	16.20	8.92E-05
27	3.93E-07	0.0	0.0	0.00	0.00E+00
28	0.00E+00	162.0	1.0	162.00	0.00E+00
29	0.00E+00	27.0	0.6	16.20	0.00E+00
30	5.72E-06	0.0	0.0	0.00	0.00E+00
31	0.00E+00	0.0	0.0	0.00	0.00E+00
32	1.89E-07	162.0	1.0	162.00	3.07E-05
33	6.31E-08	27.0	0.6	16.20	1.02E-06
34	0.00E+00	0.0	0.0	0.00	0.00E+00
35	6.94E-07	162.0	1.0	162.00	1.12E-04
36	1.94E-06	27.0	0.6	16.20	3.15E-05
37	1.39E-07	0.0	0.0	0.00	0.00E+00
38	0.00E+00	162.0	1.0	162.00	0.00E+00
39	0.00E+00	27.0	0.6	16.20	0.00E+00
40	2.02E-06	0.0	0.0	0.00	0.00E+00
			PLL =	Σ	7.67E-04