FEASIBILITY STUDY FOR QRA OF BOULDER FALL HAZARD IN HONG KONG

GEO REPORT No. 80

ERM-Hong Kong, Ltd

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. A charge is made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents as GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.

R.K.S. Chan
Principal Government Geotechnical Engineer
November 1998

FOREWORD

Since 1993, the Geotechnical Engineering Office (GEO) has been assessing the feasibility of applying Quantitative Risk Assessment (QRA) to landslide hazards in the Hong Kong Special Administrative Region. This report, published as GEO Report No. 80, presents an evaluation on the feasibility of assessing the risks posed by boulder falls using classical QRA techniques in the Special Administrative Region. In the report, a brief discussion on the factors that could lead to boulder fall initiation has been carried out together with a review of some of the boulder fall incident reports kept by the GEO. The report also includes a literature search on the available international data on risk assessment or hazard analysis of boulder falls. A practical framework and programme for the QRA of boulder fall hazards is also documented.

The study was carried out by ERM-Hong Kong Limited as consultants to the GEO of the Civil Engineering Department. During the course of the study, valuable discussions and exchange of views were held between the consultants and GEO staff especially Messrs C K Wong, H N Wong, and Ken Ho. Their contributions are gratefully acknowledged.

(S H Mak)
Chief Geotechnical Engineer/Slope Safety

EXECUTIVE SUMMARY

In Hong Kong, natural slopes exist which are strewn with boulders. Boulder falls occur occasionally and casualties or property damage sometimes result.

The GEO is preparing an omnibus paper on landslip risk which encompasses evaluation of risk of boulder falls and the cost benefit analysis of reduction of boulder fall risk. The purpose of the study is to provide input to the landslip risk management with respect to boulder falls.

The purpose of this phase of the study is to identify the feasibility or otherwise of a Quantitative Risk Assessment (QRA) of boulder falls in Hong Kong. *Appendix A* provides an explanation of the QRA process and its outputs, terminology and definitions.

The overall study may consist of four phases, i.e.:

Phase I   Feasibility Study
Phase II   Territory-Wide Preliminary QRA on Boulder Falls
Phase III Development of QRA Methodology for Individual Boulders
Phase IV   Territory-Wide Detailed QRA on Boulder Falls

Phases II, III and IV are dependent on the outcome of the Feasibility Study. Phase IV is dependent on the outcome of Phase II.

The feasibility study has included the following reviews:

- boulder fall incident data (Hong Kong and worldwide);
- data available within GEO;
- methodology (reviewing published literature relevant to boulder falls and approach to QRA).

The study finds that there is a large volume of high quality Hong Kong historical data on boulder fall incidents, but that readily available worldwide data is relatively sparse. Although no previous QRA study of boulder fall has yet been found, the literature reviewed indicates most of the key methods necessary to conduct a boulder fall QRA are available, when combined with the Hong Kong historical incident data.

A QRA of the risk of boulder falls in Hong Kong is considered to be feasible.

Two approaches to the territory wide study have been considered. The conclusion is that the simpler approach, which is based on detailed assessments of representative study areas, will be appropriate for Phase 2 of this study.

The more complex approach, assessment of the whole study area in one

model (using GIS, RISKPLOT or an interface between the 2 systems) was not considered appropriate for Phase 2 due to the major effort required to overcome technical difficulties (modelling of population and the gravitation of falling boulders to valleys). These would be developed in Phase 4. An interim Phase 3 would consider the risk from individual areas of boulders or a small study area and would develop some of the techniques required for Phase 4.

A framework methodology for the Phase 2 study has been proposed.

The Phase 2 study will provide an estimate of the risks from boulder falls. It will indicate total risks, contributors, the range of numbers of fatalities which could occur and the frequency at which these events would be expected (FN curves). The FN curves will be compared to landslide risk and other acceptability criteria and the requirement to mitigate will be identified. The contributors to the risk will be used to highlight mitigation measures and based on estimates of cost these can be screened and prioritised using cost benefit analysis.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

In Hong Kong, many natural slopes, particularly those in colluvial areas, or below rock cliffs are strewn with boulders, some of which are of enormous dimensions. Boulder falls occur occasionally, particularly during or following intense storms with heavy rainfall, with casualties or property damage sometimes recorded.

Since 1994, the GEO has been assessing the application of Quantitative Risk Assessment (QRA) to landslip hazards in Hong Kong. Following the slope Safety Review carried out by the Works Branch in December 1994, the GEO is considering preparation of an omnibus paper on landslip risk which encompasses evaluation of risk of boulder falls and the cost/benefit analysis of reduction of boulder fall risk. The purpose of this project is to provide input to the landslip risk management with respect to boulder falls.

For the purpose of the present project, some definitions are given below:

boulder a boulder is a rock fragment with a volume exceeding $0.2m^3$ existing on a natural slope. Boulder includes rock on natural cliffs but excludes rock on man made rock faces and corestones exposed as part of soil/rock excavations.

boulder fall boulder fall is the downhill movement of boulders from a natural slope as a result of soil erosion, earthquake or other causes. This term is synonymous with "rockfall" from natural slopes.

The first phase of the project is the Feasibility Study, this is concerned with assessing the feasibility of applying risk assessment techniques to boulder fall risks in Hong Kong. The second phase of the project, if feasible, involves a territory wide preliminary QRA to ascertain the levels of risk presented by boulders and estimation of the required costs for mitigation of the boulder risks, if required.

Subsequent project phases, if feasible and required, involve the development of a QRA methodology for assessing areas of individual boulder risks, and also more detailed territory wide QRA on boulder risks.

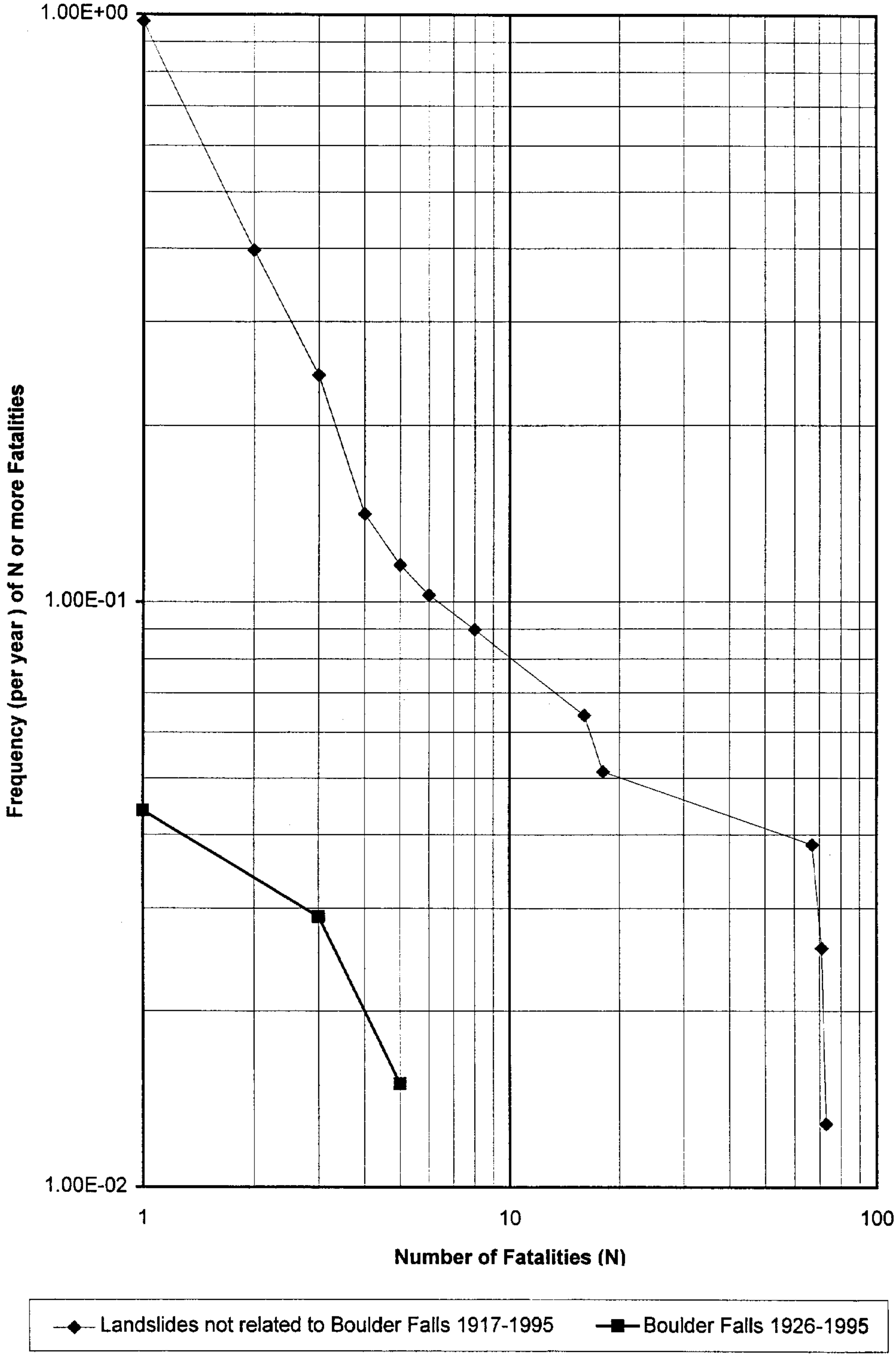
Historical Levels of Risk

During the 60s and 70s some 50 to 100 fatalities could be expected per severe storm from landslide events (including slope failures and boulder falls). This amounts to a historical Potential Loss of Life (PLL) of some 10 fatalities per year. Table 1.1a shows the landslide incidents (not related to boulder falls) which have caused fatalities during the period 1917-1995.

Table 1.1a *Historical Landslide Incidents not related to Boulder Falls 1917 - 1995*

Year	Location	Number of Fatalities
1917	St Joseph College	6
1925	Po Hing Fong	73
1966	La Salle Road	8
1966	Varies	30
1967	Tai Po	1
1968	Varies	22
1969	Varies	2
1971	Varies	5
1972	Po Shan	67
1972	Sau Mau Ping	71
1972	Shiu Fai Terrace	1
1972	Ap Lei Chau	1
1972	Belcher's Street	1
1972	Bullock Lane	3
1972	Ma Shan Village	2
1972	Nam On Fong Village	1
1972	Seymour Road	1
1972	Lan Fan Shan	1
1973	Castle Peak Road	1
1975	Hang Hau	1
1976	Varies	7
1976	Sau Ma Ping	18
1978	Tan Kwai Tsuen	1
1978	Ma Chai Hang Village	1
1979	Mui Kwong Tsuen	1
1981	Lei Yue Mun Road	1
1982	Varies	27
1983	Mount Davies	1
1989	Lion Rock Lower Village	2
1992	Kennedy Road	1
1992	Baguio	2
1993	Cheung Shan	1
1994	Castle Peak Road	1
1994	Kwun Lung Lau	5
1995	Fei Tsui Road	1
1995	Tuen Mun Highway	1
1995	Shum Wan Road	2

Figure 1.1a: Comparison of Historical Societal Risk from Boulder Falls with Landslides not Related to Boulder Falls



Considerable improvements to the safety record for landslides have been made and the historical PLL during recent years has been reduced to approximately 1 fatality per year.

There have been some 169 rock/boulder fall incidents during the 11 year period from 1984 to 1994, with 3 injuries but no fatalities. Over the last 69 years 9 deaths have occurred from rock/boulder falls. This is equivalent to an average historical PLL of 0.13 fatalities per year. In the phase 2 study, each incident report will be studied in detail and incidents other than boulder falls (i.e. rock falls from a cut slope) will be taken out.

Not all of the incidents may be recorded by GEO/GCO, however we can expect that all incidents since establishment of GEO in 1977 involving injury or fatalities will have been reported. Over the last 69 years, 3 incidents have resulted in fatalities, one at the Elliot Pumping Station, Pok Fu Lam in 1926 resulting in 5 fatalities (thought to be a $700m^3$ boulder), one in Shau Kei Wan squatter area in 1976 resulting in 3 fatalities and one in Kings Road in 1981 resulting in a single fatality. These incidents are plotted in *Figure 1.1a*. For comparison the historical societal risk from landslides and boulder falls has also been plotted.

One FN curve is plotted for landslides not related to boulder falls, for the time periods 1917-1995 and one curve for boulder falls from 1926 to 1995.

Statistically rarer more severe incidents would not have been expected to occur within the period for which records have been kept in Hong Kong.

Table 1.1b *FN Data based on Historical Landslide Incidents (not Related to Boulder Falls) 1917 - 1995 and Boulder Falls from Natural Slopes 1926 - 1995*

Number of Fatalities, N	Frequency of N or more Fatalities (per year)	
	Boulder Falls 1926-1995	Landslides on Man Made Slopes 1917-1995
1	0.0435	0.974
2		0.397
3	0.0290	0.244
4		0.141
5	0.0145	0.115
6		0.103
8		0.0897
16		0.0641
18		0.0513
67		0.0385
71		0.0256
73		0.0128

It can be seen that the societal risk from boulder falls lies significantly below those for landslides.

1.2 *OBJECTIVES*

The objective of Phase 1 of this project is to determine the feasibility of, and in later phases to carry out a Quantitative Risk Assessment of boulder fall hazard in Hong Kong with a view to assessing the current levels of societal and individual risk to the public and a cost/benefit analysis for reduction of boulder fall risk in vulnerable areas.

The overall objective for a QRA of Boulder Falls in Hong Kong must therefore quantify a range of events, providing frequency and number of fatalities for each. It will not be adequate to provide an arbitrary points scoring system for frequency and likelihood.

Supplementary objectives will be to:

- identify the range of hazards which could arise, the boulder size/shape distribution, their locations, ground conditions, etc;

- develop each hazard to the point where it has a discrete quantifiable consequence and quantify the frequencies of each discrete event or combination of events;

- explore ways to quantify the consequence with say terrain type (slope, vegetation etc) and boulder size etc to generate an expected energy vs distance plot and a maximum horizontal range;

- identify the potential population types at risk and their degree of protection or otherwise by location or building type etc.;

- apply the consequences to each relevant population for the whole territory and sum the risks to produce FN curves and PLL and if feasible calculate Individual Risk (IR) values. These would be for (i) an individual as if constantly at a given location (an area or location risk); (ii) for individuals spending time in different locations (i.e. the most at risk individual(s) and the average or typical individual).

1.3 *SCOPE OF WORK*

The study will consist of four phases, ie

Phase I	Feasibility Study
Phase II	Territory-Wide Preliminary QRA on Boulder Falls
Phase III	Development of QRA Methodology for Individual Boulders
Phase IV	Territory-Wide Detailed QRA on Boulder Falls

Phases II, III and IV are dependent on the outcome of the Feasibility Study. Phase IV is dependent on the outcome of Phase II.

1.3.1 *Phase I - Feasibility Study*

(i) Review the boulder fall incidents (documented by GEO) which have occurred in Hong Kong and the associated causes for the incidents.

(ii) Carry out a brief review of the existing available overseas data on boulder falls, including studies on risk assessment or hazard analysis of boulder falls.

(iii) Review the data available on the GEOTECS database and GIS in CED and the possibility of using this information as a basis for boulder falls QRA in Hong Kong.

(iv) Review the state-of-the-art of QRA methodology, as applicable to this project, and summarise the appropriate definitions for risk terminology.

(v) Assess the feasibility of application of QRA to estimate the territory-wide risks presented by boulders in Hong Kong.

(vi) Suggest a practical framework for QRA of boulder fall hazard in Hong Kong and prepare the programme for the QRA and estimate resources required.

(vii) Produce the Phase I Feasibility Report which includes the results of the above work. Present the report to Geotechnical Engineering Office staff in a formal presentation which includes an introduction to QRA methodology.

1.3.2 *Phase II - Territory-Wide Preliminary QRA on Boulder Falls*

Where Phase I has indicated that QRA on boulder falls is feasible, the project will progress onto Phase II to carry out a territory-wide preliminary QRA on boulder falls. A preliminary scope of work for this phase is given below, this will be firmed up in the Phase I Feasibility Study.

(i) Identify boulder fall incidents in Hong Kong which have not been reported to GEO by making reference to relevant government departments, eg Highways Department, Fire Services Department, etc. Review the causes of the boulder falls.

(ii) Carry out a literature survey on the existing available overseas data on boulder falls, including studies on risk assessment or hazard analysis of boulder falls.

(iii) Carry out a hazard identification exercise to identify the causes of boulder fall incidents and the potential consequences of incidents.

(iii) Analyze the data available in CED and, together with interviews of GEO experts, determine which areas in the territory present boulder fall risks. Compare these areas with known boulder fall incidents.

(iv) Site visits to a number of the identified boulder fall risk areas.

(v) Determine the boulder fall rate per unit area for the identified boulder risk areas.

(vi) Determine the consequences of boulder falls for each of the identified boulder risk areas, ie impact on people and property, disruption to traffic, etc.

(vii) Estimate the territory-wide boulder risk levels by combination of the calculated boulder fall rates and potential consequences of incidents.

(viii) Compare these risk levels against historical incident records in Hong Kong. Compare also against risks from other hazards in Hong Kong and against the Government Risk Guidelines for PHIs.

(ix) Carry out a brief review of the known methods for mitigation of boulder falls and their associated scale of costs.

(x) Carry out a Preliminary Cost-Benefit Analysis to estimate the required cost of mitigation measures, including investigation and assessment costs, to reduce the risk levels to acceptable levels, should the calculated risk levels in (vii) above require mitigation.

(xi) Produce the Phase II Report which includes the results of the above work.

1.3.3 *Phase III - Development of QRA Methodology for Individual Boulders*

Whereas Phases II and IV address the risks of boulder falls on a territory-wide basis, this phase is concerned with individual boulder risks. The following is a preliminary scope of work for this phase:

(i) Develop a methodology for QRA for an individual boulder on a slope. The methodology should be relatively simple to apply and should include the basic elements of QRA, ie

- Hazard Identification;
- Frequency Analysis;
- Consequence Analysis;
- Risk Summation - to calculate individual risks and societal risks to the public.

(ii) Apply the QRA methodology on 3 Case Studies for individual boulders on relevant slopes in Hong Kong. Identify potential risk mitigation measures for reduction of risk levels for each case study. Carry out a Cost-Benefit Analysis to recommend appropriate risk mitigation measures, if required, for each boulder risk case.

(iii) Compare the calculated risk levels to risks presented by other hazards in Hong Kong and to the government risk guidelines for PHIs. Comment on the acceptability (ie tolerability) of the boulder risk levels.

1.3.4 *Phase IV - Territory-Wide Detailed QRA on Boulder Falls*

Where Phase II has indicated that the risk from boulder falls is significant, there may be a need for more detailed territory-wide QRA to be carried out, in order to adequately determine the required resources/costs and mitigation measures for reducing risks to acceptable levels. The following tasks represent a preliminary scope of work for a Phase IV territory-wide QRA:

(i) Develop a methodology for detailed QRA of territory-wide risks from boulder falls. The methodology should preferably be GIS-based and use the available data within CED.

(ii) Carry out a literature review to identify available consequence models for boulder falls, eg impact models for various boulder sizes, shapes and material and various slope characteristics.

(iii) Apply the territory wide QRA model for boulder falls to determine the current risks presented to the population from boulder falls in Hong Kong.

(iv) Carry out a comprehensive review of the methods available for mitigation of boulder fall risks and their associated scale of costs. Comment on the associated benefits and problems of these methods and their practicality for implementation in Hong Kong.

(v) Carry out a Cost-Benefit Analysis to recommend appropriate risk mitigation measures to reduce risk, if required. Compare the calculated risk levels to territory wide risks from other hazards in Hong Kong and comment on the acceptability (ie tolerability) of the boulder risk levels.

(vi) Develop a specification for a computerised database which includes data on past boulder fall incidents in Hong Kong, and is suitable for input (by GEO) of details of future boulder fall incidents. Advise GEO on procedures required to ensure that relevant boulder incidents are identified by Government departments, with appropriate information passed on to GEO.

(vii) Prepare the Phase IV Report on the results of the above study.

2 INCIDENT REVIEW

2.1 HONG KONG INCIDENTS

Some 169 records of rock/boulder fall incidents over the past 11 years are held by CED. Further records may be held by FSD, Highways Department or other Government Departments. Several engineering consultants may also have relevant incident records.

For this feasibility study it was not appropriate to collect or review all of the incident records. A sample of some 17 incident records were provided by CED and reviewed. These are listed in *Table 2.1a*.

2.1.1 *Causes*

These incidents record common causes of boulder falls as:

- erosion;
- washout;
- tree root action.

Often the weather during inspection is recorded as rainy or the incident has happened following a storm or typhoon.

2.1.2 *Distances Travelled*

Figure 2.1a shows the horizontal distance D plotted against the frequency of horizontal movement of D or more. For such a small sample of incidents it has not been possible to account for the mechanisms of initiation and propagation. The flatter part of the curve is due to rocks hitting flat ground and halting, where if they had been on a hillside they might have continued to fall. This tends to suggest that horizontal distances of more than 50 to 70 metres would occur every 10 years but that larger horizontal distances could occur less frequently. Examination of a larger number of incidents would be required to substantiate this.

Figure 2.1b shows horizontal distance versus vertical distance. This is useful in establishing the likely shadow for the areas at risk. The shadow angle can be calculated by comparison of the horizontal distance travelled to the vertical distance. 80% of the boulders fall within a 50° shadow and the remaining 20% within a 60° shadow.

2.1.3 *Boulder Sizes*

For the 17 incidents reviewed, boulder sizes range up to $15m^3$. *Figure 2.1c* shows a cumulative log-log plot of boulder volume, V, versus frequency of volume V or more. The frequencies are estimated assuming roughly 15 boulder falls per year. It tends to indicate that boulders as large as 30 to $100m^3$ would be expected to fall every 10 years!

Table 2.1a: Incidents Reviewed

Ref.	Date	Time	Cause	Description of Boulder	Angle of Slope, where boulder originally located (degrees)	No. of Boulders	Boulder Dimension 1 (m)	Boulder Dimension 2 (m)	Boulder Dimension 3 (m)	Volume	Vertical Travel (m)	Horiz-ontal Travel (m)	Receptor	Damage	Location
1	23-Mar-92	night				2				1			School Playground		St Antonius Girls College, 1 Ko Chiu Road, Yau Tong, Kowloon
										1					
10	15-Mar-93	18:10	Erosion	Subangular	70	2	0.75	0.5	0.5	1	7	7.5	Access Road to residential Building		1 Magazine Gap Road
							0.5	0.25	0.25	1	7	6			
11	2-Jun-93	morning	Surface water on fill/rubbish	subround	50	1	0.7	0.5	0.5	0.2	7	5	Squatter Huts		Tai Hang Old Village, Tai Hang Road
12	16-Jun-93		erosion	subround	70	1	1.6	1.3	0.5	1	4	5.25	Access footpath to residential building		Kam Ping Mansion, 63-69 Kam Ping Street
14	17-Jun-93	15:10	surface degradation, tree roots			multiple	0.1	0.1	0.1	1.5	8	3	Temporary office hut		Opposite Marine Police Station, 28 Shum Wan Road
							0.3	0.3	0.3						
15	16-Jun-93			subround	45	1	2	2	2.5	8	3	3	Building Lot, Squatters Huts		Behind Doctors Quarters, Tung Wah Eastern Hospital near to squatters huts
16			Tree Root Action		60	1	1	0.85	0.85	0.7	42	44	Road	1/2 lane of road blocked (crossed Findlay Road, bounced on Plantation road, halted below Plantation road)	Natural Slope above Findlay Road
17	13-Aug-93	7:00	Erosion/Infiltration			1	1.5	1.5	1.5		1	2	Road	Traffic slightly affected	Junction of Tai Hang Road and Blue Pool Road
18	28-Sep-93					2				2			Footpath in remote part of Victoria Peak		Chatham Path
21	27-Sep-93	morning	Erosion	roughly cubic		1				15	24	42	Natural Slope		natural slope north of Wing Chuk Street, Chuk Yuen (north) estate
22	22-Jul-93			rounded	70	3	0.4	0.3	0.3	0.2			Squatter hut		
23	18-Sep-93	morning				2	0.6	0.4	0.4	1					Harlech Road near lamposts 24245 & 24244
							0.3	0.4	0.4				Road/pavement		
28	4-Jul-95	15:30		subrounded		1	1.15	1.2	0.6	1	3	2	Retaining wall near residential building		15 New Eastern Terrace, Tin Hau Temple Road
29	4-Jul-93	8:15		sub angular	40	3	1.35	0.9	0.6	2	33	35	Car Park	4 private cars damaged	Natural Slope behind Kingsford Garden, 202-216 Tin Hau Temple Road
							1.35	0.8	0.65		36	35	Residential Block		
							1.3	1	0.65		39	35			
32	14-Jul-95	morning	washout	angular, broke into 2 pieces	40	1	0.3	0.15	0.15	0.2	10	12	fenced off area below slope		Natural slope behind building contractors Association School, 62 Tin Hau Temple Road
							0.35	0.22	0.15						
33	13-Jul-95		infiltration, washout	subangular	40	2	0.8	0.55	0.4	0.5	3	5	open space, beach		Stanley Main Beach (rocky 100m cliffs to N)
							0.76	0.5	0.45		3	6			
34	3-Aug-95		erosion	rectangular		1	1	1	0.5	0.5	10	8	water tank in urban area		Slope behind Kiangsu-Chekiang College, 30 Ching Wah Street, North Point

Figure 2.1a: Frequency of Horizontal Distance Moved by Boulder

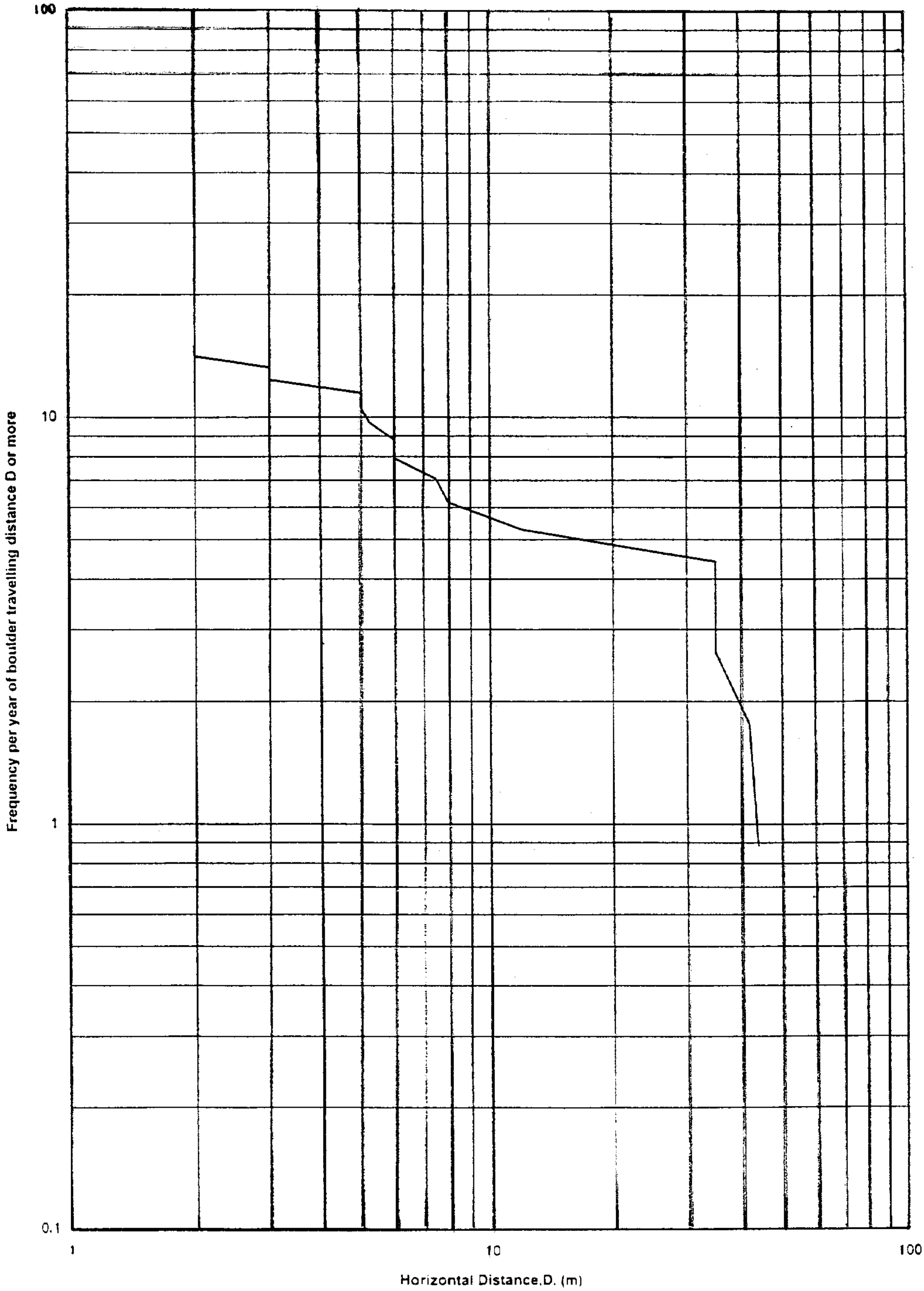


Figure 2.1b: Horizontal versus Vertical Distance travelled

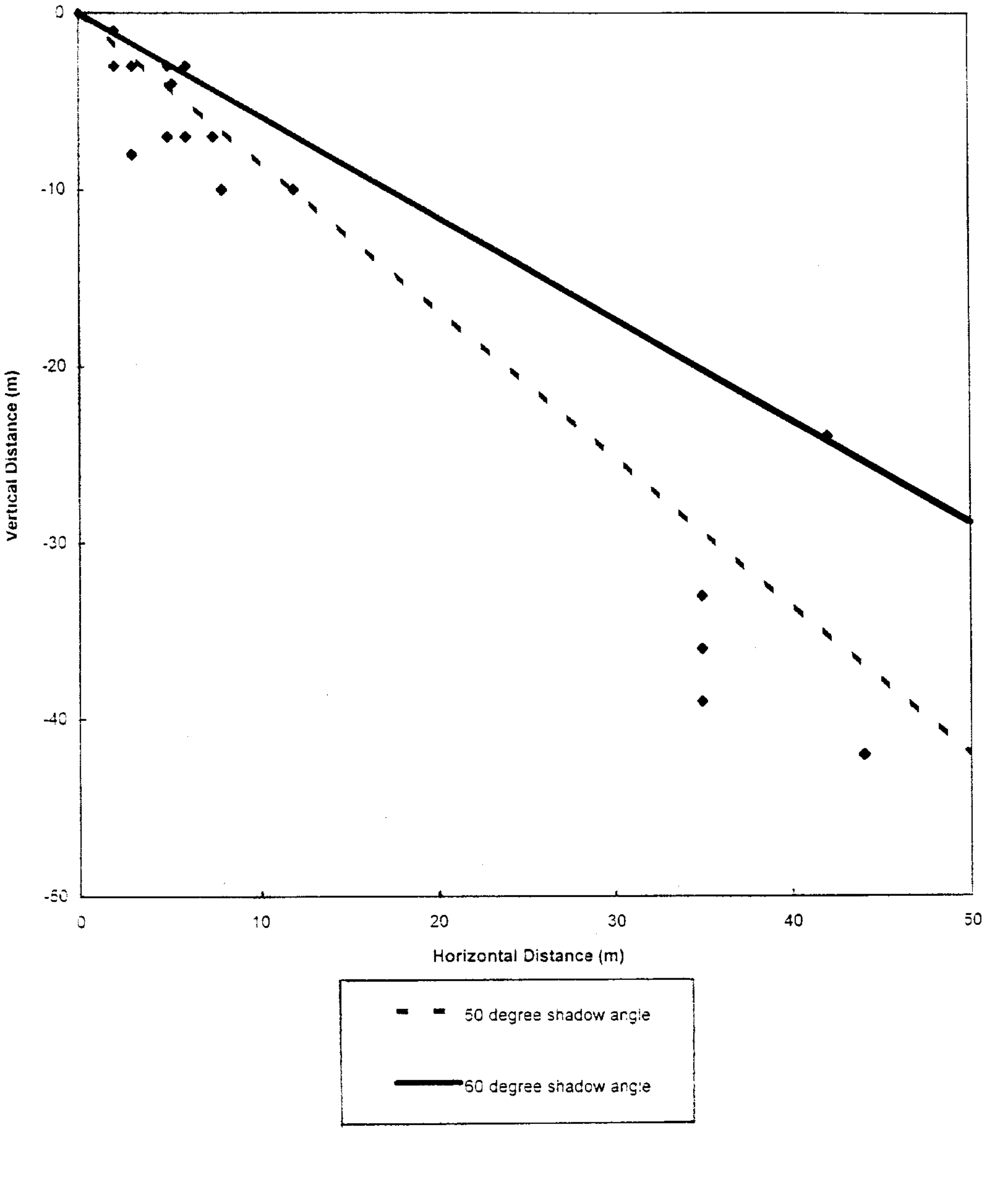
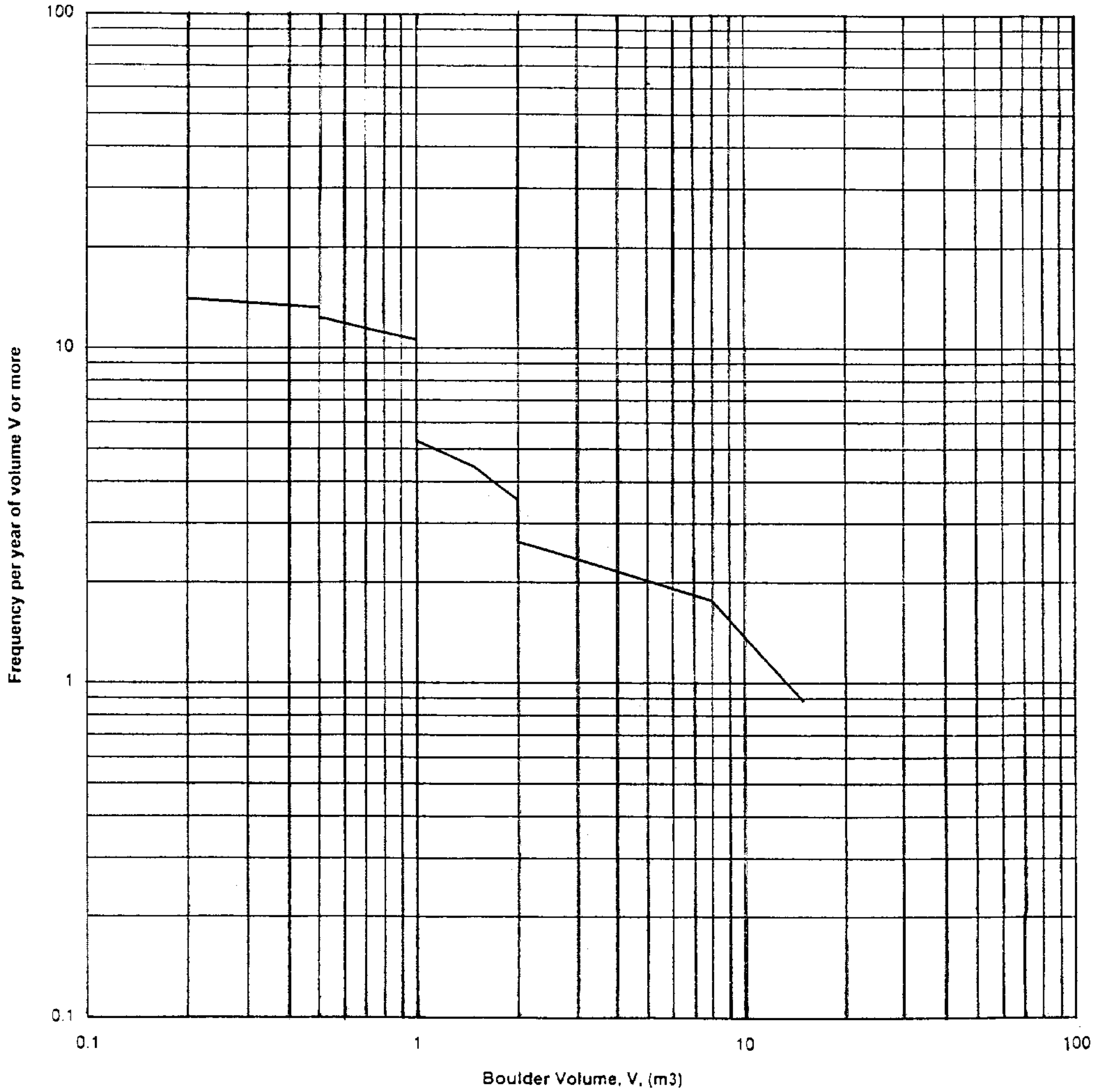


Figure 2.1c Boulder Size Frequency



This estimate would be refined by review of a larger number of incidents which might indicate a maximum expected boulder size.

2.1.4 *Receptors*

The receptors or targets of the boulder falls from the 17 incidents reviewed are as follows:

- School Playground
- Residential Block
- Squatter Huts
- Temporary office hut
- Building Lot
- Car Park
- Access footpath to residential building
- Road/pavement
- Retaining wall near residential building
- water tank in urban area
- open space, beach
- fenced off area below slope
- Footpath in rural part of Victoria Peak
- Natural Slope (boulder did not reach developed area)

The order of the above list is in rough order of potential severity of consequence, had a larger or faster moving boulder fallen. No severe consequences were recorded for any of the 17 incidents.

2.2 *Worldwide Incidents*

Data searches of MHIDAS, a worldwide industrial major accident database, have been carried out and whilst a small number of landslide incidents have been identified, no boulder fall incidents were found.

One rockfall incident is documented in MHIDAS;

- In British Columbia, a rockslide caused derailment of 16 tank cars containing methanol. Two tank cars fell from the cliff into a river and one spilled its entire contents, the other spilled a large quantity. Several other tanks were damaged by rocks and had minor spills. No fire resulted but residents had to stop using drinking water.

The literature review contains details of a number of worldwide incidents, see *Sections* 4.2.2 and 4.2.4.

3 GEO DATA REVIEW

The Civil Engineering Department has a wealth of data on landslides and boulder falls. Much of this is in the form of the incident reports reviewed above. However, there is no complete information or data available in GEO to show the boulder locations in the territory and the main characterisation of all individual boulder areas.

4 METHODOLOGY REVIEW

4.1 DEFINITIONS

Appendix A gives an introduction to quantified risk assessment with terminology and definitions applicable for boulder fall QRA.

4.2 LITERATURE REVIEW

4.2.1 *Assessment of Risk from Rockfall from Active and Abandoned Quarry Slopes*

Author's Abstract

Rockfall is a significant hazard in quarries. An account is given of the findings of recent assessments of the risk from rockfall from faces in working and abandoned quarries using computer simulation techniques. Methods of calibrating the rockfall models based on field experiments to determine coefficients of restitution and thereby assess critical bounce heights and roll distances are also discussed.

Consultant's Review

Robotham et al. [1] report on a study applied to quarries. The slopes from which rocks are falling are near vertical and thus for heights of 325m horizontal distances of no more than 65m are predicted. This study is useful background only.

4.2.2 *The Assessment of Rockfall Hazard at the Base of Talus Slopes*

Author's Abstract

Fragmental rockfall is characterised by the independent movement of individual rock fragments after detachment from a rock face. The continued operation of the process leads to the accumulation of talus slopes. On talus slopes the rockfall shadow extends beyond the base of the talus and consists of scattered boulders that have run out beyond the base of the slope. The landing probability of boulders in the shadow is examined; return periods of the order of 1000 years relative to the house site are typical. Rockfall behaviour particularly with respect to run out into the shadow can be assessed using geological evidence, empirical methods, physical modelling, and computer based analytical methods. An empirical minimum shadow angle of 27.5° (i.e. the angle between the distal limit of the shadow and the top of the talus slope) is suggested and would be useful in rockfall vulnerability studies at the base of talus slopes as a first approximation to shadow limits. It is preferable to the use of the rockfall fahrboschung as proposed by several authors. A random collision lumped mass model (ROCKFALL) is outlined. ROCKFALL uses two restitution coefficients and a transition to rolling criterion. ROCKFALL is used to analyze two fatal rockfall accidents in southern British Columbia, at Hedley in 1939 and Sunnybrae in 1983, which are documented in detail. An additional non-fatal incident is also analyzed (Barnhartvale in 1974). Results based on an initial calibration were encouraging. Documentation of the three rockfall incidents shows that, in each case, rockfall fragments impacted on homes at equivalent shadow angles of 30° or more. This would suggest that a review of existing development within rockfall shadow areas at the base of talus slopes may be in order.

Consultants Review

Evans and Hungr [2] provide a wealth of information all either directly or indirectly relevant to the modelling of boulder falls in this study. Their case studies are based on cliffs, valleys and vegetated talus slopes in British Columbia. Perhaps the most relevant information is the comparison of rock velocity, horizontal and vertical distance and fragment volume. The study covers fragment volumes up to $100m^3$ and predicts horizontal distances up to 30m and velocities of around 30m/s.

They also state that the upper limit (although not well defined) for low magnitude fragmental rock falls (as opposed to larger rockfalls) is 10^5 m^3. The rockfall statistics for Canada record some 4 deaths in houses and 9 deaths on transportation routes in this century. He mentions a rockfall in Italy which caused 8 deaths in Lecco.

4.2.3 *Rockfall Evaluation by Computer Simulation*

Author's Abstract

By using a probabilistic approach, a model was developed for predicting the distance that bouncing rocks will travel down a slope. Field data on rock bounce characteristics were used to compute the coefficient of restitution. A computer program called 'ROCKSIM' was produced to predict rockfall impact areas by using the coefficient of restitution and kinematics of free-fall and rolling motion. The ROCKSIM predictions were used to evaluate the effectiveness of the proposed remedial measure to mitigate the hazard. This preliminary application indicated that ROCKSIM may be a useful tool for evaluating the rockfall process in other areas. Additional data will be collected for model calibration.

Consultant's Review

Wu [3] describes a particular application, the falling of rocks onto Interstate 40 in North Carolina, for a computer model for the trajectories of falling rocks. The paper presents the equations of motion and experimentally determined coefficients of restitution. The paper concludes that shifting the roadway laterally by 24 feet will isolate the roadway from virtually all rockfall (the roadway starting some 50 feet from the base of the slope).

4.2.4 *Morphostructural Evolution and Related Kinematics of Rockfalls in Campania (Southern Italy); a Case Study*

Author's Abstract

On the southern slope of the Sorrentine peninsula there are many subtriangular depressions in which the main towns of the area are located; the depressions are linked to block-rotation during strike-slip fault activity and are often marked by high subvertical cliffs and related rockfall phenomena with consequent damage to the underlying towns. On the basis of back analyses carried out using Hoek's method, an in-depth study of some of the rockfalls enabled us to define for one of these towns the most suitable shock restitution coefficients of the detritical pyroclastic deposits present on the terraces situated at the foot of the cliffs. On the basis of the main kinematic parameters of actual rockfalls and approximately 6600 simulated rockfalls, a plan was drawn up of the valley bottoms which were at high rockfall risk. The size of the high-level rockfall risk sites depends above all on the presence, number and size of the terracings where citrus fruit trees are cultivated. The calculation method suggested by Paronuzzi was also adopted in order to make a detailed evaluation of the role the terraces play in modifying the trajectory height, the translation velocity and the endpoint of the boulders. Although there are methodological and statistical differences between the two methods, results from both studies showed sufficient correlation, in particular concerning the trajectories' endpoints.

Consultant's Review

Budetta and Santo introduce their paper giving reference to rockfalls damaging the town in 1401, 1588, 1764 and 1780. The rockfalls were generally initiated by heavy rain or earthquakes.

The paper describes the geology of the location in detail. They provide details of 2 boulder falls.

In 1991 a $1.4m^3$, 3.65 tonne elongated polyhedral-shaped boulder fell from a height of 100m above sea level. The rock mass followed an initial free fall trajectory with secondary impacting on areas of roughness on the cliff. It rebounded past 2 citrus fruit terraces and came to rest on the third approximately 50m above sea level. The boulder fell some 50m and travelled some 20m horizontally.

In 1986, a rock slide induced block fell from a height of 20m and shattered at the foot of the cliff. The estimated speed of the boulder was 20m/s on impact.

The author describes computer simulation programmes by Hoek [5] and Paronuzzi [6] and uses these to simulate the actual incidents and to carry out hazard zonation of the area. The hazard was generally found to be limited to within 20 to 35m of the foot of the slope. A comparison was also made between normal slopes at the foot of the cliffs and terraced slopes. In the simulations, boulders inevitably came to a halt beyond the end of the normal slopes; but for terraced slopes about 64% of the trajectories came to a halt on the first 2 terraces, 31% on the third and fourth and only 5% end up at the toe of the slope.

4.2.5 *Analysis of Rockfall Hazards at Los Alamos National Laboratory*

Author's Abstract

In the early years at Los Alamos National Laboratory, rockfall hazards were intuitively recognized and avoided. Hence mesa tops were selected over canyon floors for construction sites, although some canyon bottoms were still used. The Omega West reactor site was located in a narrow portion of Los Alamos Canyon adjacent to 400 foot high vertical cliffs. In 1944, a quarter-mile long rock catcher was installed above the reactor to protect the facility from occasional rockfalls. In addition, an annual rock catcher inspection was initiated. Between 1944 and 1993, 24 separate rockfall events were documented; individual rocks trapped in the catcher ranged in size from 300 to 21,000 pounds.

These rockfall inspection data were arranged into an annual exceedance series, and a frequency analysis was performed. This type of analysis is routinely employed in flood studies when stream gauging records are available. Prior to this study, however, such techniques had never been used with rockfall data. This analysis indicates that the annual rockfall series is approximately log-normally distributed, and that the 500-year rockfall event will probably exceed 187 tons. In addition, a Markov generation scheme, which preserves the statistics of observed logarithms from the historical data, was used to generate a synthetic rockfall series. These synthetic data suggest that the cliff face will retreat at an average rate approximating 2 to 3 centimetres per 1000 years. This rate is comparable to independently computed rates that range from 4 to 14 centimetres per 1000 years. These cliff-face erosion processes are important because they affect mesa-top trench burial operations of low-level radioactive wastes.

Consultant's Review

This paper describes in general terms with some equations, the approach taken to establish the size versus frequency distribution for rock falls in a given location, based on only 24 rock falls and a period between 1959 and 1970 including 15 of these when the time of the fall was not recorded. A computer program was used for the analysis and it is suspected that there is insufficient information provided in the paper to reproduce the analysis. The authors predict a 187 tonne rock would fall every 500 years, which they verify, based on the geology of the area is possible. This work is extremely encouraging and provides pointers to the approach which can be used in Phases 2, 3 and 4.

4.2.6 *Stemming Rock Falls*

Author's Abstract

The factors that cause rockfalls include: fracture orientation; blasting; water and ice pressures; tree roots; weathering; and traffic vibration. To minimize the number of accidents caused by rockfalls, techniques have been developed to identify potentially hazardous areas, and to design and construct remedial measures. Rock slope stabilization measures are divided into 2 categories: rockfall control techniques and slope stabilization techniques.

Consultant's Review

The author makes the surprising observation (applicable to the study areas to which it is referring) that rockfalls are more common than landslides and more readily mitigated. The paper is in fact considering cut rock faces and not boulder strewn slopes. Nevertheless some valuable pointers to suitable mitigation measures are provided.

4.2.7 *Geologic Analysis of Rock Deterioration at Selected National Park Service Archaeological Sites: Rock Motion Hazard*

Author's Abstract

The purpose of the report is to provide some advance awareness of rock motion hazards (rockfall, slump, glide, and creep). A reconnaissance trip was made during the period May 8 to 16, 1978 under contract to the Western Archaeological Centre, Tucson. The reconnaissance was to provide geologic perceptions of rock deterioration problems at the sites noted and to identify peripheral geologic problems that may threaten the sites or their safe operation.

Consultant's Review

This paper concerns natural rock faces and is of little relevance to this study. It examines mechanisms for rock movement and its measurement and involves field trips tracking minute movements of rocks which may or may not be significant. The paper contains details of some rockfall incidents and voices concern regarding the hazard posed by actual rocks up to 100 tonnes.

4.2.8 *Rockfall Modelling and Attenuator Testing*

Author's Abstract

Two rockfall attenuator designs were constructed and tested in a valley near Rifle, CO. The first device was based on railroad ties hanging from a cable and the second device used tires mounted on rims and stacked over pipes which were hung from a cable. Both of these devices were designed, not to stop the rocks but to slow them down to a point where they would not be a hazard. The devices were tested by rolling rocks, weighing between 500 and 6000 pounds, down the slope. The tests provided needed data for further design of such rockfall attenuators and validation of the rockfall model developed by the Colorado School of Mines and the department. The rockfall computer program, which simulates rocks tumbling down a slope, predicts the statistical distribution of speed and bounce height, and can be used for locating and designing rockfall barriers. The model takes into account the slope profile, rebound and friction characteristics of the slope, and spinning energy of the rocks. Both spherically and disk shaped rock can be simulated.

4.2.9 *Consultant's Review*

The paper describes work done using a 2 dimensional rockfall simulation programme, referred to as CRSP. This was used to examine attenuator design, i.e. the slowing down of falling boulders rather than stopping them completely. Two examples of attenuator were examined: one consisting of hanging strips of metal and the second from used car tyres. The paper also includes examples of actual incidents.

The theory of the simulator is extremely well documented in the user manual which is included with the paper. The source code is also included. This paper is likely to be invaluable in Phases 3 and 4, however it may provide too much detail for Phase 2.

4.3 *State of Art QRA Methodology for Boulders*

Work in the field of rockfalls includes a number of main themes:

1) postulation of mechanisms often including presentation using GIS to show high risk areas;
2) estimation of frequency versus size in site specific case study;
3) computerised modelling of trajectories;
4) combination of 1 and 3 (without quantification of risk in absolute terms) to identify (in relative terms) high risk areas, often using GIS;
5) identification of mitigation measures.

No literature documenting a full QRA on boulder falls has been found in this limited survey.

4.3.1 *Mechanism of Initiation and Sources of Boulders*

The Consultants are not in a position to judge the quality of work done on mechanisms of initiation and possible sources of boulders since this requires detailed examination by Geotechnical Engineers or Geologists. Knowledge of the mechanisms causing boulder falls is valuable since it gives insight into the means by which the risk from boulder falls can be mitigated.

The factors influencing the initiation of boulder falls are not as well known as those for landslides. Robotham et al [1] highlight that the UK HSE investigate the causes of rockfall in quarries and rainfall is found to be a major factor. Clearly there must be rocks or boulders at or close to the surface. The slope of the terrain must also be a factor.

Detailed knowledge of the mechanisms of initiation may not however be essential and may be established empirically by inspection of incident data in Hong Kong for example.

The large amount of historical incident data available in Hong Kong is sufficient to indicate the majority of frequent boulder sources. These more frequent sources would also be expected to be the more significant in terms of risk. Historical data alone would be sufficient to provide basis for a QRA model. Detail would be added by modelling of known or postulated sources or causes of boulder falls. The disadvantage of using postulated models is that it may not be possible to weight the significance of different mechanisms properly against each other and against the historical data.

Inspection of the base of slopes, by geotechnical specialists in known rockfall areas should also provide information on past rockfall incidents which have been unreported, especially so in remote unpopulated areas. This information could be very useful for size distribution analyses.

4.3.2 *Frequency Estimation*

The work done on frequency estimation, primarily by McLin [7], appears to have been based on a small number of rockfalls, some 24 only. The incident data in Hong Kong provides a much larger number of incidents than this and it is envisaged that this technique can readily be reproduced.

4.3.3 *Trajectory Modelling*

Rockfall simulation programmes, often incorporating Monte Carlo simulation (see *Appendix A*), have been developed by a number of authors. It is pointed out by some that the equations of motion are well established and others provide tables of coefficients of restitution and other data by which to calibrate these models.

A number of options are available, either:

- one or more of these programmes could be obtained from the authors;
- a simulation programme could be written from scratch;

an empirical model based on incident data could be generated.

For the phase 2 study, the latter approach is favoured since the former two approaches would have to be calibrated against the incident data in any case and little benefit is gained from the complex modelling.

One of the main benefits from the modelling would, however, be the estimation of the velocity of the boulder, which, combined with its size will identify its energy and thus will indicate the damage which it could inflict for example to a building or elevated road.

4.3.4 *Assessments Quantifying Frequency and/or Consequence but not Risk*

A number of studies have been carried out to date which assess (in relative or absolute terms) consequences and/or frequency but do not quantify risk in absolute terms. In some cases risk is quantified by means of a prioritisation scheme but not in absolute terms.

The frequency/consequence assessments carried out to date provide encouragement that much of the data required for full QRA is available on GIS at least for some parts of the world. Full QRA using GIS may be technically feasible, in terms of memory requirement, run time and programming. The favoured approach is to investigate this during Phase 3 of this study with a QRA of an individual boulder.

4.3.5 *Mitigation Measures*

The options for mitigation of boulder fall risks have not been reviewed in detail at this stage, a large number of papers cover this area and undoubtably describe high quality practical options for risk mitigation.

5 FINDINGS

5.1 INTRODUCTION

The view taken during the preliminary discussions between CED and the Consultants prior to commissioning of this work, was that since the number of boulders in the territory was not known, and hence the frequency of an individual boulder fall was not known, a study of an individual boulder was less feasible than a territory wide study.

The discussion in this section therefore focuses on the feasibility of a territory wide Boulder Fall QRA study.

5.2 FEASIBILITY

A QRA of Boulder Falls will require the following main stages to be carried out:

- hazard identification;
- frequency estimation;
- consequence modelling;
- risk summation;
- acceptability of risk and evaluation of mitigation measures.

Hazard Identification

The main input to the hazard identification stage is provided by historical data, literature survey and expert knowledge. All of these are readily available, either within GEO or the Consultant's experience.

Frequency Estimation

The frequency estimation stage can be based on frequency estimates or adjustments quoted in literature but this is unlikely to provide Hong Kong specific frequency estimates. Better is to use the historical data.

The Hong Kong historical data provides good records of a very large number of incidents and the completeness of the sample can be established. This is extremely good in comparison to worldwide data for boulder falls and incident records upon which frequencies for chemical risk assessments are based. It is also very good in comparison to the number of incidents used by others in boulder fall frequency estimation exercises.

The historical data provides a good indication of the sources of boulders in the territory. It may not include all sources of boulders. Some of the sources which are not included could be significant due to the size of boulder or the nearby population.

The inclusion of postulated mechanisms (based on expert knowledge) will fill in many of these gaps. We have only one hypothesis in a suitable form for inclusion in the study at present. In addition to the known mechanisms of erosion, tree roots, washout or similar, other possible hypotheses are that boulder falls may be initiated by:

- development work (cutting of slopes, excavation, vibration);
- hill fires removing vegetation, drying out soil and causing shrinkage.

Consequence Analysis

The literature survey has identified several existing models for boulder fall trajectory and a number of models exist for estimating the damage caused by boulder impacts. Equally, there is a large volume of evidence within the historical data which could also be used for predicting the behaviour and effects of falling boulders.

Risk Summation

The simplest method of risk summation, is carried out manually. The risk assessment of installations on Tsing Yi, completed in 1982, were carried out in this way and many consultants without suitable risk integration software still carry out risk assessment in this way.

Some consultants have developed general and specific software for carrying out this labour intensive stage. Generally the algorithms are relatively simple and if not already available such software can be readily developed.

Acceptability of Risk and Evaluation of Mitigation Measures

Strictly it is not always necessary to establish the acceptability of a particular level of risk in absolute terms, although number of established techniques for doing this are within the Consultant's experience. The acceptability of the risk is readily established by considering whether there are practical, cost effective means available to reduce the risk. This is referred to as the As Low As Reasonably Practicable (ALARP) principle. The cost effectiveness being established by consideration of the value of human life.

The evaluation of mitigation measures would be carried out by rerunning the risk summation for the new case. Ranking of measures would be done using the ALARP principle described above.

General Feasibility

In general terms the QRA of boulder falls in Hong Kong is considered to be feasible, since there is a wealth of historical data in Hong Kong, frequency and consequence models can be based on the historical data or consequence software models can be used. The remaining areas of a QRA are well within the Consultant's experience.

Alternative Approaches

Two alternative approaches to such a territory wide study are possible:

1) choose a number of representative or typical locations throughout the territory which illustrate the risks from boulder falls. Carry out a risk assessment of each of these areas. In order to establish the territory wide risks, factor up and weight accordingly (the weighting process is discussed in more detail later in the *Risk Summation* section of *Section 5.3.1*);

2) by some method, for example GIS and/or RISKPLOT (the Consultant's risk integration software), model risks for whole territory. Based on the information reviewed above, detail of proposed approaches and their feasibility are discussed. To place the proposed approaches in context, each is only as good as the data on which it is based. The data is good enough to provide size distribution and territory wide frequency. The literature provides a good basis for consequence modelling.

5.2.1 *Representative Locations*

This approach has the advantage that individual case studies would be able to go into significant important detail, for example:

- the precise locations of buildings, roads, and other vulnerable areas;

- several of the study areas could focus on the issues perceived to be high risk; and could include areas where CED are considering mitigation measures (to demonstrate their cost effectiveness);

- the scope for graphical integration of the risk (i.e. manual risk assessment rather than using computer models) - this is an advantage since the hazard footprint of a falling boulder is not readily modelled in chemical risk assessment software - the main problem being the realistic modelling of the focusing of the risk at valleys;

- the overall frequencies and risks for more frequent incidents could be calibrated to historical experience.

The main disadvantages are that because the study is not looking at the whole territory;

- it could overlook an area of high risk;

- risks to individual vehicles may require additional consideration; often the population on a road is considered as an average (persons per day), the risk as plotted on an FN curve should reflect the range of possible fatalities, i.e. the boulder could hit a double decker bus, a minibus or a motorbike etc. or a pile-up could result;

- the weighting and adding of each study area to give territory wide risks may not be accurate;

- the source location of boulders will only be modelled for the study areas and so territory wide blackspots will not be identified;

- this approach may not provide meaningful individual risk contours; (whilst an estimate of individual risk for a small number of locations within the study area may be produced, individual risk contours, normally generated by risk integration software considering a very large number of locations and interpolating, will be difficult to generate by a manual approach);

- study areas may need to be large or there may need to be a large number of them to include all of the key features.

5.2.2 *Single Model of Whole Territory*

The advantages of this approach would be:

- the software would rapidly assess the risk for the whole territory and combinations of high frequency and population would not be overlooked;

- individual risk contours could be produced if RISKPLOT were used and these would assist in locating high risk areas;

- the risk results could be grouped by source location or boulder size for example to identify the dominant contributors and hence mitigation measures;

- the Topography feature of RISKPLOT may be of use in ensuring that the risks from boulders are focused down hill;

- risks to individual vehicles on roads would be properly modelled automatically within the software since they can be considered as having the actual numbers of passengers per bus or car (rather than an average number of passengers per km of road);

- the model would be set up so that as further hypotheses were accepted they could be readily included into the model and the risk assessment rerun.

The main disadvantages of this approach are:

- the focusing of the risk at valleys may not be properly modelled;

- it would be necessary to model all population within a few hundred metres of the sources of the boulders throughout the territory (a major task).

5.3 *SUGGESTED FRAMEWORK*

The two disadvantages of the territory wide study are so significant that, to overcome them, a larger timescale and effort than is possible in Phase 2 of this study would be necessary.

The territory wide approach in a single model should be reserved for Phase 4, during which a more detailed review should be carried out of the scope for adapting RISKPLOT, interfacing with GIS and/or carrying out the risk integration using GIS.

As a pilot study for the detailed QRA of the whole territory, a pilot study of a single boulder or a single location should be carried out in Phase 3. This would establish a model for the trajectory and consequences (as a function of source and terrain) and impact, which would be suitable for use in Phase 4.

It is not clear at this stage whether the Phase 4 model would be a conventional probabilistic model or a Monte Carlo simulation.

5.3.1 *Proposal for Phase 2*

The approach proposed for stage 2 is to select a number (say 4 to 6) of representative or key study areas. The full set of study areas should include examples of schools and hospitals, different ages of buildings, different types of roads, footpaths providing access to residential sites, etc. A QRA of boulder falls in each of these areas would be carried out and the results of these combined by factoring and weighting appropriately to provide an estimate of the territory wide risk.

The approach would include the following stages.

Data Collection

Data to be collated would include:

- a comprehensive set of boulder fall incident records;
- data on population numbers and locations and the locations of buildings, roads etc. Information on age of buildings will provide insight into the quality of construction and hence the vulnerability;
- the terrain in each study area.

At this stage, a catalogue of incident locations would be built up and plotted. This would assist in selection of the study areas. This plot would also be used to highlight areas which were frequent sources of boulders.

Hazard Identification

This stage will be included for completeness and will include an overview of the causes listed in the incident files and causes highlighted in the literature.

Frequency Estimation

The incident data will be analyzed to establish a distribution of frequency versus boulder size and distance travelled. Based on the areas identified from the incident location plot a frequency per unit area of boulder source would be established.

Consequence Analysis

The incident data will be analyzed to establish the probability for various shadow angles.

The rockfall simulation models will be used to establish the velocity of falling boulders and existing models for impact of objects with structures will be used to model the vulnerability/damage caused versus boulder size.

The incident records will be examined for any evidence of persons being hit by boulders and not being killed. Otherwise a probability of death of 1 will be assumed.

Risk Summation

Appropriate thresholds will be identified from the consequence analysis which will be used to divide the size versus frequency distribution up into representative ranges of events. For example:

- small boulders which would not do sufficient damage to cars or buildings to cause a fatality;
- medium size boulders which could kill a person in a car but would not damage a building;
- large boulders which would punch through a wall in an older building or a non-reinforced structure such as a squatter hut or partially demolish a building;
- massive boulders which would demolish a whole building.

Secondary hazards such as pile-ups on roads or impacts of boulders on PHI sites would be considered for each threshold level.

Boulder shadows would be modelled for each of the size ranges and all significant boulder source locations. For each case the frequency and consequences would be calculated and recorded.

This information would be summarised and presented as an FN curve and a total PLL, also broken down by contributing case. It may also be possible to extract meaningful information on levels of individual risk.

Estimation of Risk for Whole Territory

The risk profiles for each study area will be factored, weighted and added together, by calibration against the incident records to give an estimate of the risks for the whole territory.

The main parameters which will be used to factor and weight the study area results are:

- the historical frequency and size distribution of boulder falls for the whole territory;
- the historical risk (which the high frequency, low fatality end of the resulting FN curve for the whole territory would be expected to match);
- the population at risk (within the shadow angle of boulder sources) in the whole territory and the numbers of key features (roads, squatter huts, residential buildings, playgrounds etc.);
- the size and density distribution of boulder source areas.

Assessment of Acceptability of Risk and Mitigation

The risk estimates will be compared to suitable criteria used for assessment of other risks, also against levels of risk from similar natural hazards and conclusions will be drawn regarding the acceptability of the risk and the need to mitigate.

Mitigation measures will be highlighted and subject to availability of cost estimates from CED or from the literature, these measures will be screened and prioritised using cost benefit analysis.

Number/choice of study areas

The incident records examined so far indicate that areas at risk include:

- Tin Hau Temple Road
- The Peak
- Tai Hang
- Yau Tong
- Tsz Wan Shan
- Aberdeen

Some or all of these will be selected and supplemented with areas, perhaps including a section of the Tuen Mun highway, KCR and MTR to provide a balanced selection of study areas.

Timescale

It is envisaged that a draft report would be produced for Phase 2 of the study within 8 weeks of instruction to proceed.

6 CONCLUSIONS

A Quantitative Risk Assessment of the risk of boulder falls in Hong Kong is considered to be feasible. This is facilitated by the large number and high quality of incident records of boulder fall incidents in Hong Kong.

In advance of the study, it was considered to be more feasible to conduct a territory wide study than one for individual boulders as the number of boulders in Hong Kong was not known.

Two approaches to the territory wide study have been considered. The conclusion is that the simpler approach, which is based on detailed assessments of representative study areas, will be appropriate for phase 2 of this study.

The more complex approach, assessment of the whole study area in one model (using GIS, RISKPLOT or an interface between the 2 systems) was rejected for Phase 2 due to the major effort required to overcome technical difficulties (modelling of population and the gravitation of falling boulders to valleys) and would be developed in Phase 4. An interim Phase 3 would consider the risk from individual areas of boulders or a small study area and would develop some of the techniques required for Phase 4.

A framework methodology for the Phase 2 study has been proposed in *Section 5.3* and the details will be submitted separately for GEO consideration.

The Phase 2 study will provide an estimate of the risks from boulder falls. It will indicate the range of numbers of fatalities which could occur and the frequency at which these events would be expected (FN curves). The FN curves will be compared to landslide risk and other acceptability criteria and the requirement to mitigate will be identified.

The study will also indicate the total risks and the contributors to the total (PLL). The contributors to the risk will be used to highlight mitigation measures and based on estimates of cost these can be screened and prioritised using cost benefit analysis.

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Appendix A

Introduction to Quantified Risk Assessment (QRA)

1 INTRODUCTION TO QUANTIFIED RISK ASSESSMENT

1.1 INTRODUCTION

Hazard assessment is a mature field which has been applied in the oil and gas, chemical, nuclear, transport, other fields and now the geotechnical field. The most detailed form of hazard assessment is Quantified Risk Assessment (QRA) which quantifies the frequencies and consequences of all possible hazardous outcomes and combines these to give a number of numerical results which provide the basis for decision making. These decision making processes include:

- comparison of risks with criteria;
- choice between options;
- identification of risk mitigation measures;
- identification of the maximum justifiable expenditure on risk mitigation;
- ranking of measures according to cost benefit;
- land use planning.

1.2 QUANTIFIED RISK ASSESSMENT

The most detailed type of risk assessment is the Quantitative Risk Assessment or QRA. This is a method of obtaining a measure of performance with respect to a safety objective, which has been primarily developed as a tool to assess large scale accidents, which by their very nature are rare, and therefore their frequency of occurrence and consequence cannot be obtained from statistics alone. The QRA technique is in widespread use in the onshore oil, gas and chemical, offshore, transport and nuclear industries, being applied in the areas of conceptual design, siting, official approval, detailed design, and safety reappraisal.

QRA is used to provide measures of risk which can be used in a Cost Benefit framework, to support decisions about the safety measures to be applied to the system under consideration.

1.2.1 *Introduction to Risk Assessment*

A QRA considers all the possible accidents or outcomes which could arise in the system, the likelihood or frequency of each and its corresponding consequence (for example, in terms of the number of fatalities). Studies of more complex activities can generate very large numbers of outcomes when the precise scenario and location are taken into account. The resulting information, essentially the scenario, location, frequency and number of fatalities (or fatality rate) can then be summarised and presented in suitable form.

The calculated level of risk can be compared with the criteria available and recommendations made regarding acceptability. Appropriate detail in the presentation of the results, see *Figures 1.2a* and *1.2b*, will identify dominant contributors to the risk, in particular in areas which may be less acceptable in comparison to criteria. In this way conceptual risk reduction measures are highlighted.

In order to place the risks being quantified in context the Dutch Government in its document "Premises for Risk Management" presents a table of annual mortality rates for certain occurrences, this is reproduced below:

Annual Mortality Rate Associated with Certain Occurrences and Activities in the Netherlands

Event	Annual Mortality Rate
Drowning as a result of a dike collapse	10^{-7}
Bee Sting	2×10^{-7}
Being Struck by Lightning	5×10^{-7}
Flying	1.2×10^{-6}
Walking	1.85×10^{-5}
Cycling	3.85×10^{-5}
Driving a Car	1.75×10^{-4}
Riding a Moped	2×10^{-4}
Riding a Motorcycle	10^{-3}
Smoking Cigarettes (1 packet/day)	5×10^{-3}

The levels of risk quantified in the above table have been assessed solely by statistical methods based on the number of deaths amongst the population of the Netherlands over several years. For rare major accidents which expose only a fraction of a nation's population, risks to an individual may fall within the range above but there will rarely be sufficient statistical information available to allow the level of risk to be evaluated without recourse to other techniques.

A number of approaches are possible in order to generate the list of possible accidents described above; these are the classical approach based on event tree analysis or innovative accident simulation methods using for example the Monte Carlo Method. (many of the rockfall simulations use this method.) Simulation methods have been used for incorporating engineering and human factors considerations in a number of studies; this approach can provide a less pessimistic and more detailed set of outcomes.

Risk Assessment Objectives

The objectives of a QRA are:

- to quantify, using appropriate measures of risk, the risks associated with the system being assessed

- to compare these with the available risk guidelines and make recommendations as appropriate, or if no guidelines are strictly applicable to the situation being assessed, to define or provide suitable guidelines for benchmarking purposes

- to recommend and evaluate, as appropriate, practical risk reduction measures to bring the level of risk to either within acceptable limits or to a level as low as reasonable practicable.

Measures of Risk

QRA is used to establish the risks to both populations offsite (the general public) and onsite (the persons operating or controlling the system). Risks to onsite populations are commonly handled separately from those to offsite populations because workers at an installation can be considered to be voluntary takers of risk. In the case of landslides or boulders, the voluntary risk takers might be CED or FSD personnel or their contractors. The criteria which apply to onsite risks are different and less stringent than those for offsite risks.

Societal Risk

Societal risk considers the risk from an installation or activity to society as a whole, generally excluding the risk to onsite populations or voluntary risk takers. A number of measures or representations of societal risk are possible; the most commonly used of these are the Societal Risk or FN curve and Potential Loss of Life (PLL) - also referred to as Rate of Death (RoD).

Societal Risk or FN Curve

The societal risk or FN curves expresses the risk to the population in the study area as a whole, independent of geographical location. It is a graphical representation on a log-log scale of the frequency, F, of N or more fatalities plotted against the number of fatalities, N. The shape of an FN curve and its level (i.e. the F values for a given N) indicate the pattern and level of risk. The experienced analyst will recognise typical FN curves such as those for installations storing large quantities of LPG, where rare but catastrophic fireball events often dominate the picture. An example of a FN curve is shown in *Figure 1.2a*.

PLL or RoD

A second important measure of Societal Risk is the Potential Loss of Life (PLL), which also expresses the risk to the population in the study as a whole and for each scenario and its location. The PLL for a basecase and 2 mitigation options is shown in *Figure 1.2b*. This is an integrated measure of Societal Risk used worldwide (including use by the UK Health and Safety Executive) for assessing contributors to risk. The PLL is the sum of the outcome of multiplying each accident frequency with its associated number of fatalities:

$$PLL = \sum F_1 N_1 + F_2 N_2 + F_n N_n \ldots$$

Individual Risk

Individual Risk (IR) expresses the risk to a single person. A number of ways of considering individual risk to on and offsite individuals are possible.

Isorisk contours

The iso-risk contour (also known as individual risk contour) plot expresses the risk to the individual in 2 dimensions. An example of an IR plot is shown in *Figure 1.2c.* The individual risks at all locations are evaluated and contours for levels of individual risk specified by the analyst are plotted an a map of the study area. The normal basis for the plot assumes that an individual remains in a location constantly, thus allowing the reader to interpret the plot according to the proportion of time real individuals are actually present (the occupancy). For example, in a recent study it was found that the levels of risk in comparison to the guidelines were unacceptable as a result of possible impacts by ships carrying dangerous goods on bridge piers. The unacceptable level of risk did not extend to the land either side of the bridge and therefore considering occupancy to be low, the risk was deemed to be acceptable.

Iso-risk contours have a specific application in land use planning. Proposed developments can be excluded from areas where risk is unacceptably high.

Onsite Worker Individual Risk

Onsite worker risk or Fatal Accident Rate (FAR) is calculated based on time spent in each area of installation (occupancy) and the level of individual risk for each of those areas. The individual risk for a particular worker can thus be established. For many studies the IR for an average worker and a most at risk individual are evaluated.

Comparison of Levels of Risk with Available Guidelines

Many countries throughout the world, including the UK, Netherlands, Hong Kong and Australia, have developed risk criteria or guidelines (RG) applicable to specific types of installation. A number of worldwide RGs are shown in *Figure 1.2d.*

RGs will usually identify a level of risk which is unacceptable or intolerable, a level of risk which is acceptable or negligible and for some countries a third range is defined which lies between these two, the ALARP region, within which risks must be reduced to levels As Low As Reasonably Practicable.

RGs for IR are generally in the form of a single value specifying a threshold. The Dutch Government has defined the maximum individual risk which is acceptable from any source to be 10^{-6} per year, and from all sources to be 10^{-5} per year. The UK criterion similarly specifies the maximum additional risk to which an individual should be exposed as 10^{-5} per year whatever the source.

Intolerable levels of risk for onsite workers or voluntary takers of risk vary between 10^{-3} per year and FARs of 52 per 10^{8} hours worked (this is the upper intolerable limit for the UK HSE) although a target level for the chemical industry would be 2 per 10^{8} hours worked.

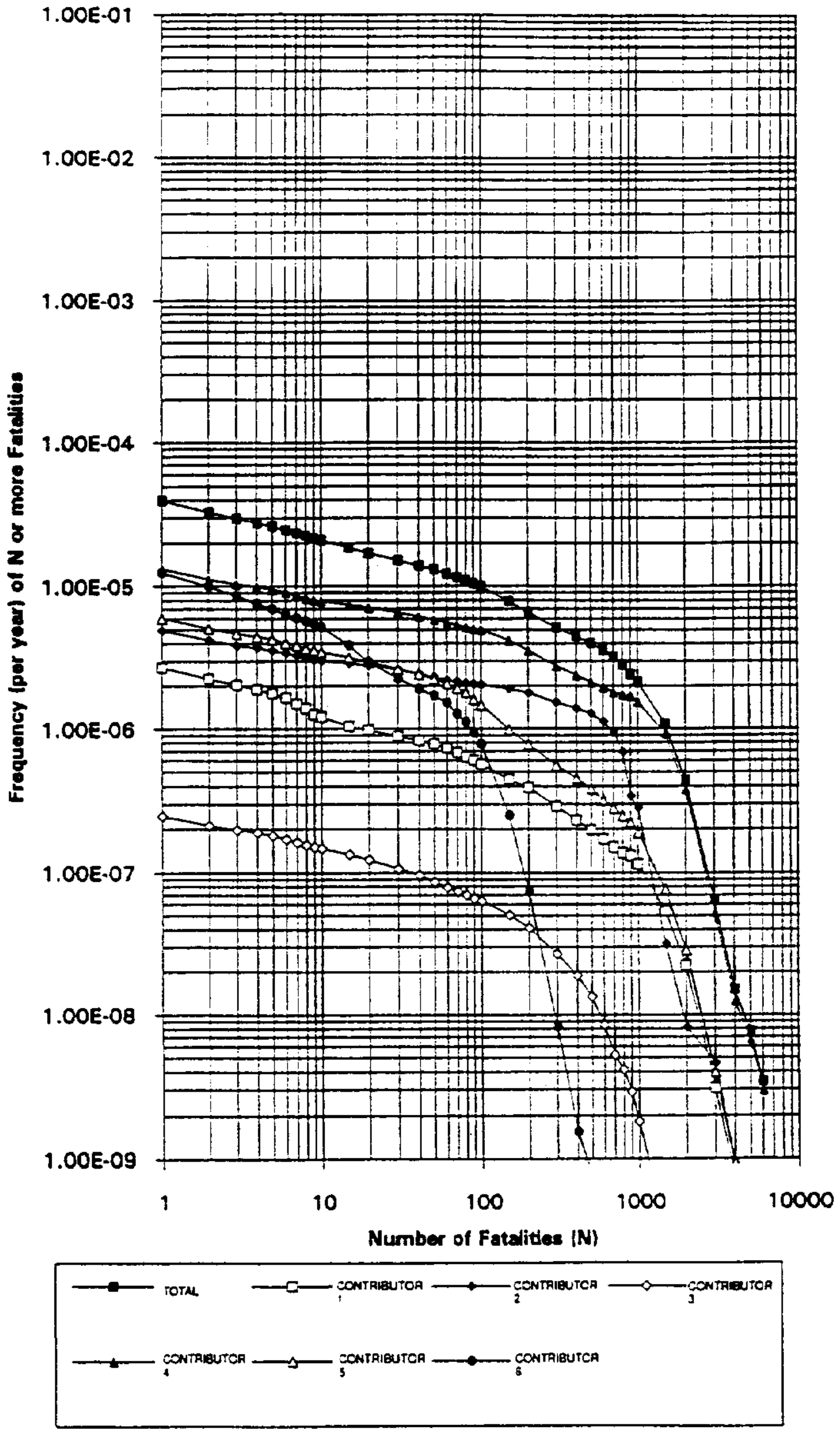

FIGURE 1.2a - CONTRIBUTION TO SOCIETAL RISK

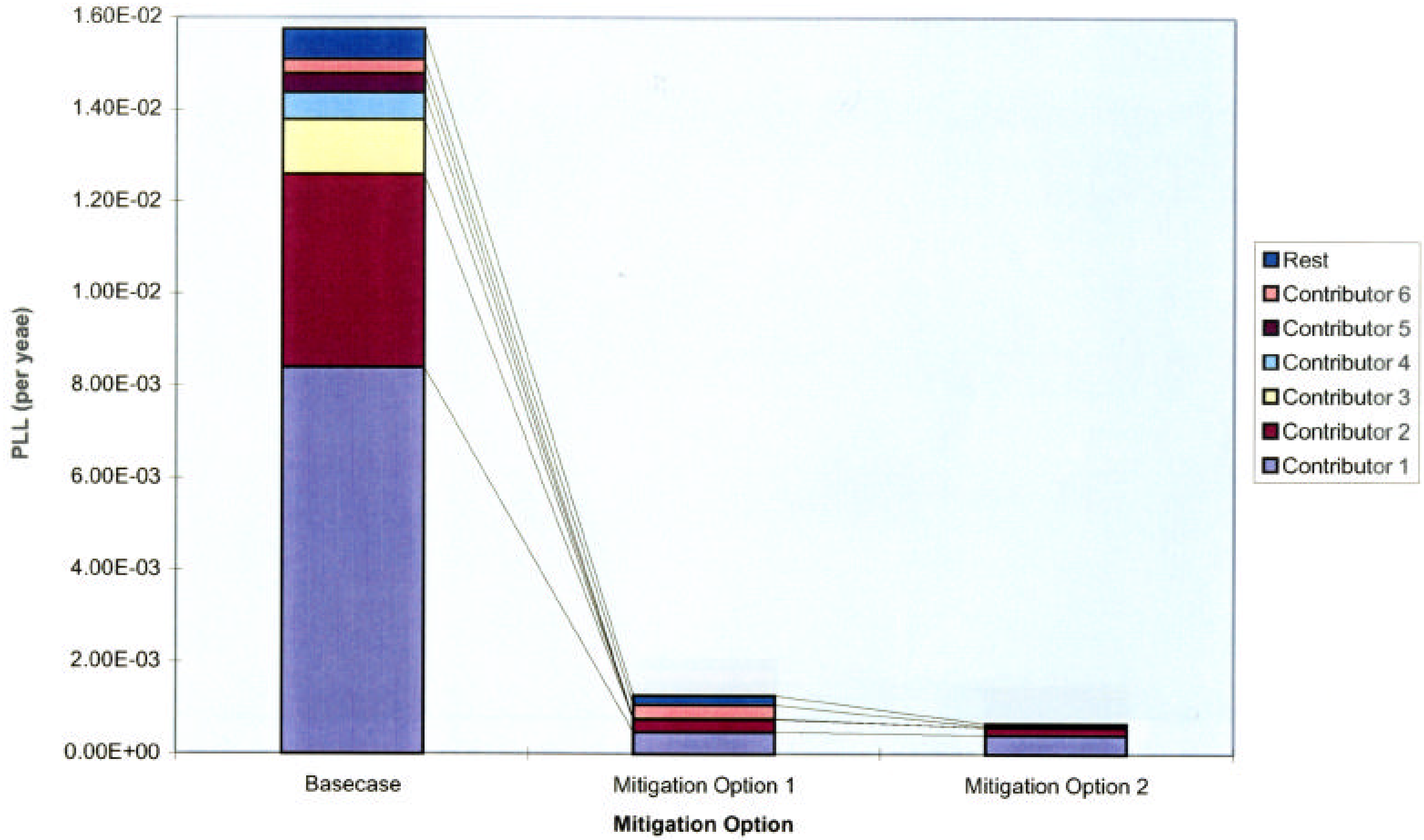

FIGURE 1.2b

COMPARISON MITIGATION OPTION SHOWING CONTRIBUTION OF SCENARIORS TO PLL

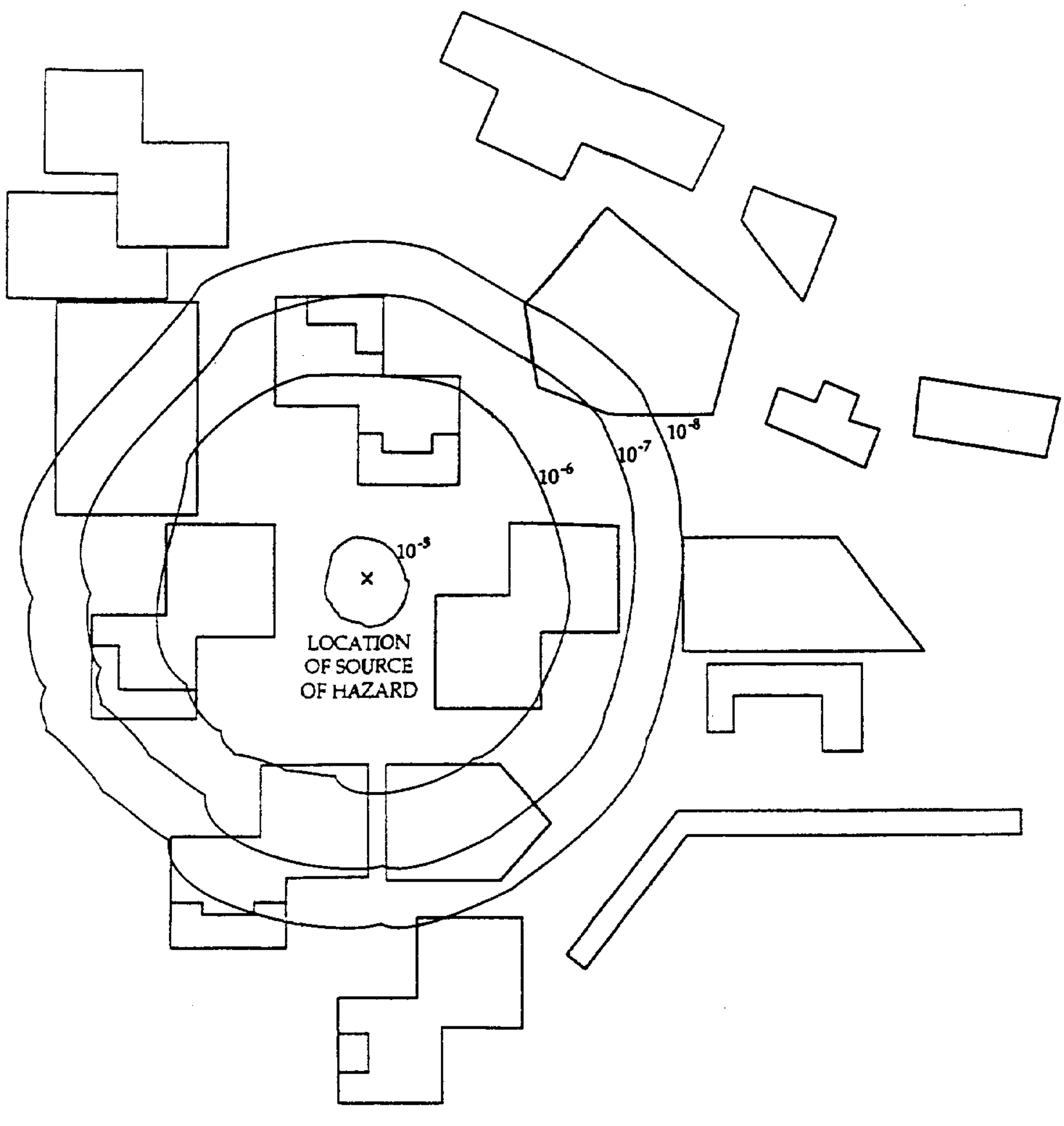

FIGURE 1.2c - INDIVIDUAL RISK CONTOUR PLOT
(SHOWING POPULATION AREAS AND
RELEASE LOCATIONS)

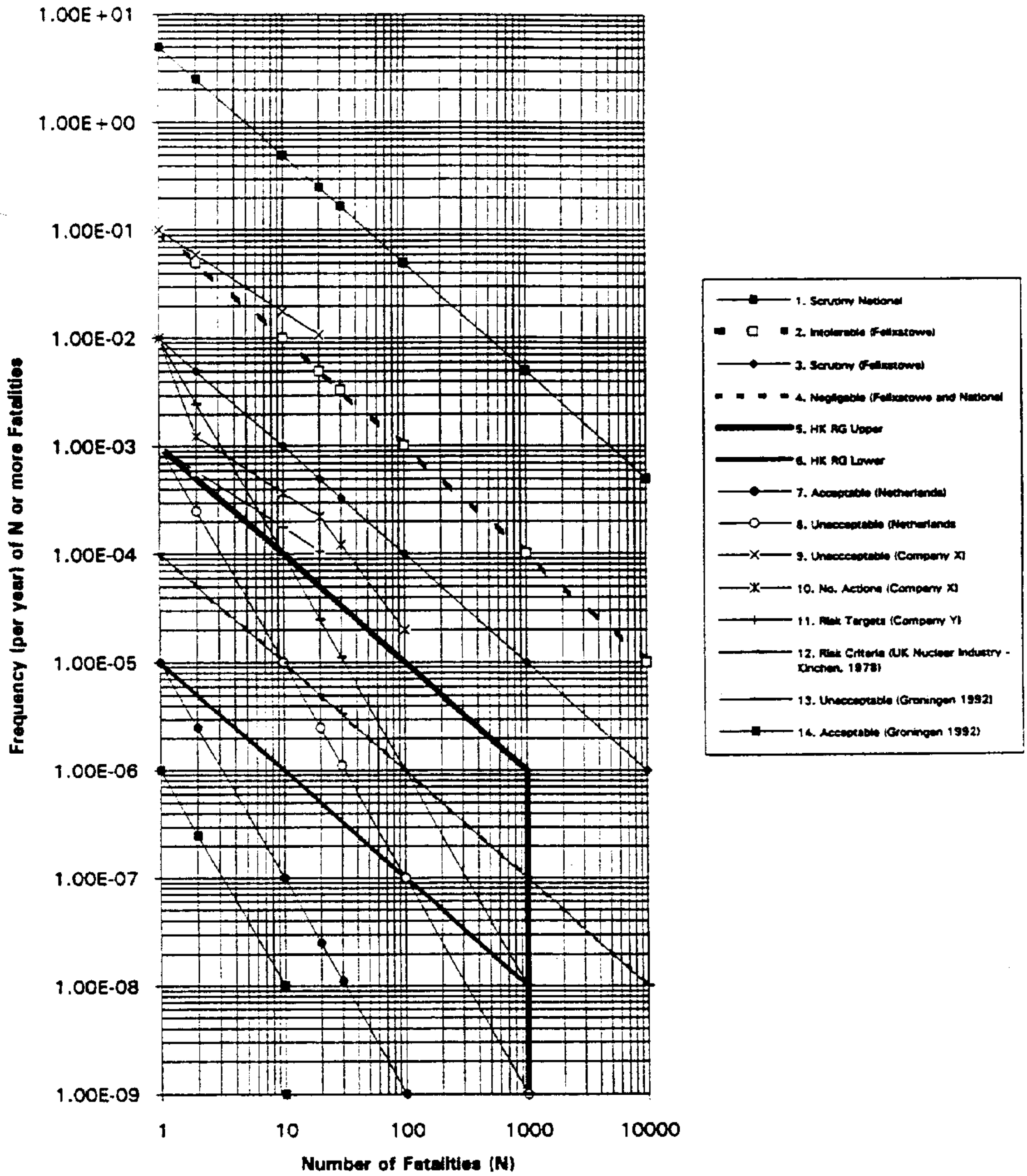

FIGURE 1.2d - COMPARISON OF INTERNATIONAL RISK GUIDELINES

LEVELS OF RISK AND ALARP

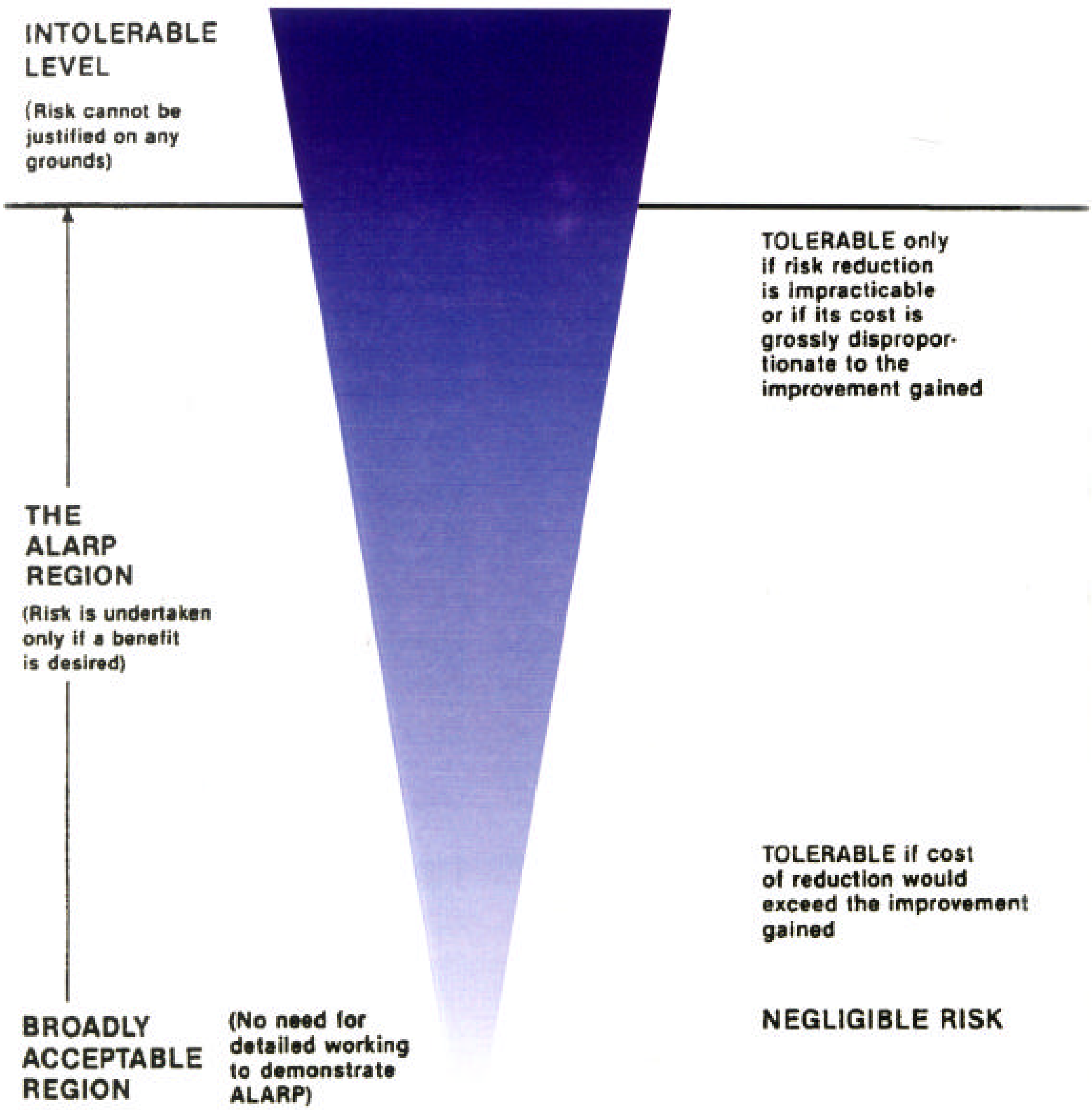

FIGURE 1.2e

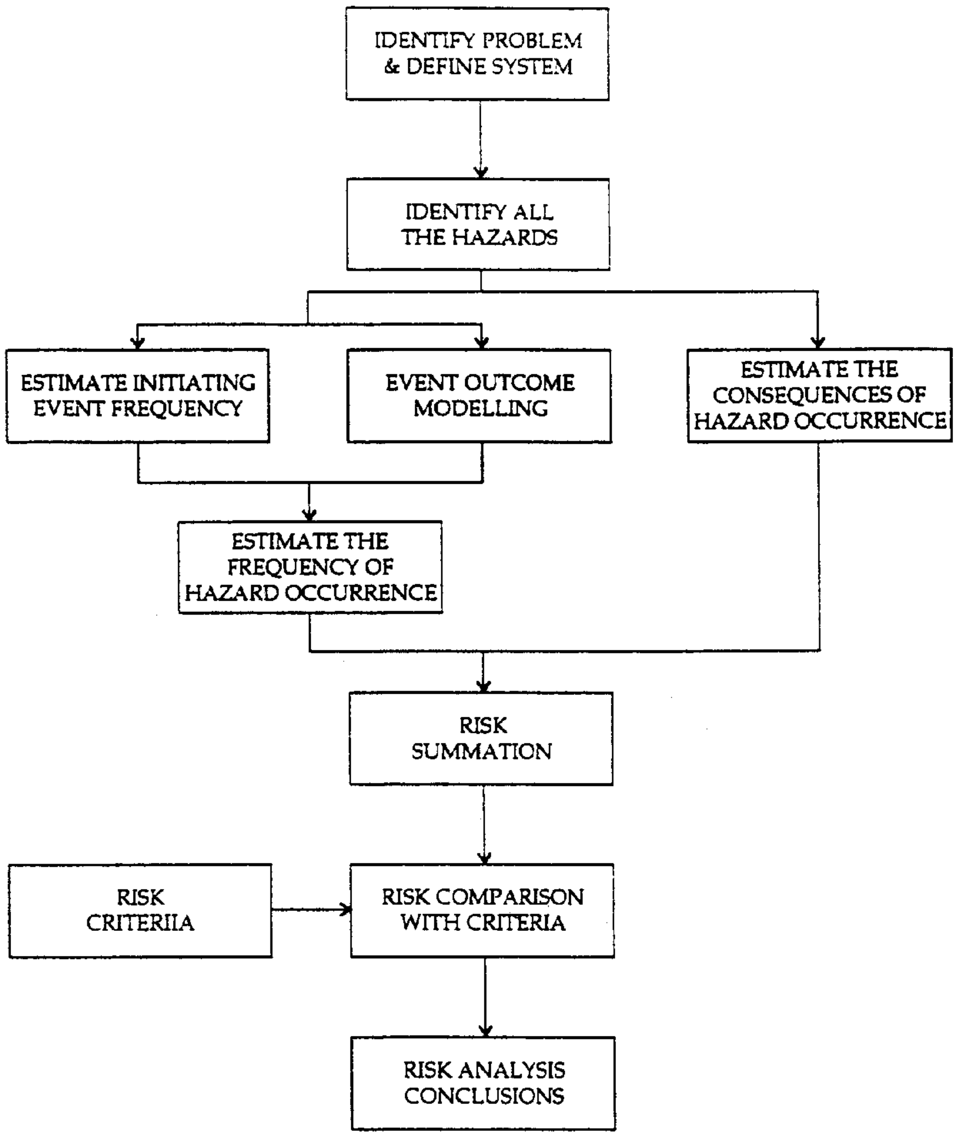

FIGURE 1.2f - MAIN STAGES IN QRA

ALARP and Cost Benefit

The reasonable practicality of risk reduction measures is established primarily by consideration of cost versus risk reduction achieved. Preliminary selection from a wide range of conceptual measures will be done by consideration of technical practicality, i.e. can this be engineered, if we do this will the operation be impaired? The ALARP principle is illustrated in *Figure 1.2e*.

A particularly informed approach as to what degree to mitigate to and on which measures to consider has been proposed by the UK government's Health and Safety Executive. It is essentially based on a cost-benefit approach.

Methodology

Cost effectiveness of mitigation measures can be assessed on the basis of the financial cost of the measure against an equivalent saving made in the numbers of lives saved in the event of an incident. This assumes a value must be placed of a human life. The following is based upon the HSE's assumption that a life is worth £2 million (allowing to some extent for 'gross disproportion').

The HSE ALARP guideline and associated cost guidelines for evaluating mitigation measures are used here to highlight the level of justifiable cost and the most opportune areas for expenditure. The HSC Advisory Committee on Dangerous Substances document Major Hazard Aspects of the Transport of Dangerous Substances (1991) gives a value of £2 million per life saved per year and suggests an assumed aversion factor of 20 for accidents where large numbers of fatalities are possible. This aversion factor represents the possible aversion to accidents which cause multiple fatalities, exhibited by society and decision-makers. The £2m per life reflects the nominal value attached to a life (using UK Department of Transport values) and an associated cost for non-fatal injuries and property damage.

It is suggested that, after taking account of the gross disproportional cost of an accident, an expenditure of £2 million may be justified for each life saved (i.e. for a reduction of 1 in the PLL per year) although an aversion factor of 20 may be used for multiple fatality accidents. Thus, a cost of between £20 million and £400 million may be justified for a reduction in PLL per year of 1 for a facility with a ten year operating life, depending on whether the PLL arises from a single event or the addition of 20 single fatality events.

Land Use Planning

A means of planning land use is provided by the individual risk contours. Given a criterion such as the requirement for levels of individual risk to be below 10^{-5} per year, it is possible to ensure that developments do not proceed that will expose residents to levels of risk in excess of this limit.

In Hong Kong, landuse planning in the vicinity of PHIs is also regulated by use of the societal risk guidelines. Since population densities are often high in Hong Kong, the societal risk guidelines tend to have a greater influence on land use planning than the guidelines relating to individual risk. The HK RGs require that the risk to a new development in the vicinity of a PHI site should normally be "acceptable".

1.2.2 *Types of Risk Assessment*

Dependent on the type of study, the requirements of the client and any regulatory body or government department and the availability of statistical data one of a number of available risk assessment techniques may be used. These techniques fall broadly into the categories of classical QRA and accident simulation. Other risk assessment techniques such as HAZOP, Failure Mode and Effect Analysis and other qualitative or semi-quantitative approaches can provide a preliminary analysis giving a general indication of the hazards or the likely source of risk.

Classical QRA methodology

The classical approach to QRA is shown in *Figure 1.2f*. This technique, which is in widespread use in the nuclear and chemical industries in the USA and Europe, is the most universal and comprehensive type of safety assessment. In the full classical QRA approach, the objective is to quantify the risk of an entire industrial operation. The main stages of this approach are as follows:

1) *Hazard and Failure Identification:* - The objective of this stage is to identify all of the failure cases, the list must be complete and non overlapping. Methods used for failure case identification include: checklists, brainstorming, **HAZOP** and **FMEA.**

2) *Frequency estimation:* - Failure or initiating event frequencies may be estimated from historical failure rate data for components, statistics on extreme events such as earthquakes and aircraft crashes and (where the system in question is complex) from a detailed examination of the possible causes of system failure due to a range of mechanisms, typically carried out by means of **Fault Tree Analysis**, described below. These initiating events are developed into a larger set of outcomes with distinct consequences which can be evaluated in terms of a fatality rate. This is done by means of event trees, described below.

3) *Consequence Analysis:* - This means using theoretical models of chains of events such as discharge of hazardous materials, dispersion in the air, ignition, explosion, fire and so on. (In the case of boulder falls - boulder trajectory models, etc.) A large range of well-tested models exists for this purpose and development is continuing in this area. These are often referred to as source term, effect and probability of death models which consider the rate of release of a hazardous material, the extent of its effect and the probability of fatalities at a particular location, respectively.

4) *Risk summation and evaluation:* - This step involves summing the likelihood and consequence information derived in steps 2 and 3 above, and

expressing the total risk in a form which suits the decision-making process which the QRA will support. There are many possible ways of presenting risk information. If, for example, the decision problem under consideration is a choice between competing design concepts, risk indices may be generated for each of the alternatives and then compared.

Data Requirements

Typical data requirements would be population numbers and their movements, maps or layout plans of the study area, incident records, details of safety measures in place. If the site were industrial then the throughpout and storage capacities on site and the site operating procedures would be relevant. If a boulder field were being considered then details of boulder type, size, density, vegetation and the angle of slope would be relevant.

Fault Trees

This techniques deals with the likelihood of failures of complex systems. In general, the technique involves constructing a "logic diagram" which expresses the interaction between components in a system, and the ways in which an abnormal condition in one component may cause abnormalities elsewhere in the system, or combine with other abnormalities to create a total failure. An undesired or unsafe condition of the system as a whole is first postulated, then the immediate causes of that condition are identified, then the causes of those causes and so on until every causal chain has been followed to the level of basic component failures (this is sometimes referred to as the "top-down" approach).

Event Trees

In the case of **Event Tree Analysis**, the logic diagram starts with a postulated initiating event, and then develops all the possible outcomes that might follow from that event, depending upon other circumstances (this is sometimes called a "bottom-up" approach). The simple objective of the tree being to develop each event to a point where the consequence of the outcome can be evaluated in terms of fatality rate by an available technique.

1.2.3 QRA Maintenance

Safety Case regulations in many countries throughout the world require that Safety Cases should be periodically updated and resubmitted. This requirement has become known as QRA Maintenance or the "living QRA".

Along with periodic maintenance safety cases must be updated whenever there is a material change in the status of the installation. The most important parameters or circumstances which affect the risk pattern of the installation and therefore require update of the QRA, include the following:

- The occurrence of a very high fatality incident;
- Major technological innovation in safety engineering;
- Discovery or better understanding of hazard;

- Change in system;
- Changes in population levels;
- changes in GEO policy for the management of geotechnical risks.

As a general observation, computer based QRA models (rather than manually calculated QRA models) will offer the best options for efficient QRA maintenance.

1.3 *DEFINITIONS*

The review of terminology for landslide risk assessment has primarily been based on the UK Institute of Chemical Engineers' (IChemE) *Nomenclature for Hazard and Risk Assessment the Process Industries* [1]. BS4778 [4] and The Royal Society's *Risk Analysis, Perception and Management* [5] have also been reviewed and comparisons are made between definitions and terminology where appropriate. Where there is likely to be an established geotechnical definition of a term, we have generally not provided a definition in order to avoid any conflict with established use.

In general it was found that the terminology presented in The Royal Society Report was identical to that in BS4778. Any significant differences between the definitions porvided by the 3 sources are highlighted below.

It is to be noted that terminology used to date in landslide hazard assessment in Hong Kong has confused the terms probability and frequency and that hazard assessments have been qualitative and have not involved Quantitative Risk Assessment (QRA).

1.3.1 *Boulders*

boulder a boulder is a rock fragment with a volume exceeding 0.2cu.m existing on a natural slope. Boulder includes rock on natural cliffs but excludes rock on man made rock faces and corestones exposed as part of soil/rock excavations.

boulder fall boulder fall is the downhill movement of boulders from a natural slope as a result of soil erosion or other causes. This term is synonymous with "rockfall" from natural slopes.

1.3.2 *Hazard and Risk*

Unlike the common usage of the terms ***hazard*** and ***risk***, in hazard assessment these terms are not synonymous.

hazard a physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these.

BS4778 does not use the word physical and includes the consequence of economic loss. The Royal Society provide a more philosophical introduction, highlighting "a situation in particular circumstances" and harm to humans or damage to physical or biological entities.

risk	the likelihood of a specified undesired event occurring within a specified period or in specified circumstances (i.e. per year or per severe storm). It may be either a ***frequency*** (the number of specified events occurring in unit time) or a ***probability*** (the probability of a specified event following a prior event), depending on the circumstances. (BS4778 specifies the combination of frequency and consequences and later defines economic and environmental risks.)

Varnes and Fell define ***Natural Hazard*** to mean the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon. This term is imprecise and should be avoided. The terms frequency and risk should be used instead.

societal risk	the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified ***hazards***.
individual risk	the frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified ***hazards***.

IChemE, BS4778 and the Royal Society provide identical definitions for ***individual*** and ***societal risk***.

1.3.3 Consequences

It is not directly the subject of this study to postulate the mechanisms of damage. However the following discussion is provided in order to introduce some terms.

Under certain circumstances a landslide can be sufficiently intense as to damage property or infrastructure (i.e. buildings). There are similarities between the front of the moving solid material and the ***shock wave*** from an explosion.

Most landslides except the most minor will have the potential to cause fatalities, either due to crushing or by ***asphyxiation***.

The above constitute the ***consequences*** of an incident, which constitute the level of damage resulting and do not include any measure of how frequently the level of damage would be expected. The consequences of an accident can also include property damage, business loss, infrastructure problems etc.

consequence analysis	is the quantification of the impact of the consequences of an incident.

One such level of damage is a specified *probability of death*. Although in the event of a landslide this tends to be an inevitable localised effect of the landslide rather than a factor which is calculated by detailed modelling (as for chemical hazards).

Another such level of damage would be the *destruction of buildings*.

BS4778 and the Royal Society do not provide any guidance on consequence terminology.

Varnes [2] and Fell [3], define ***Vulnerability*** to mean the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. He expresses this on a scale from 0 (no damage) to 1 (total loss). Jones defines the term ***vulnerability model*** as the mathematical models applied in the estimation of hazard range.

The definition by Varnes and Fell is a useful concept which has already been addressed in the specific case above where the set of elements are people, by the term ***probability of death.*** The definition provided by Varnes and Fell is that of a probability and should be termed ***probability of (a given level of harm or damage)*** in specific cases.

There are other aspects to this concept. Persons at risk will spend only part of their time in a given location and have scope for escape to areas which are more protected. For example, a risk assessment may assume that persons spend a proportion of their time in different locations (indoors, out of doors, cars etc.) and using the out of doors situation as the baseline, they will have increased protection in the other areas. This introduces the concept from Morgan et al [6] of the probablity of temporal impact (i.e. of house occupancy) given the spatial impact; this is more commonly referred to as the ***occupancy*** in Hong Kong. For the more protected areas, a ***protection factor*** is defined for each, which is a number between 0 (fully protected) and 1 (unprotected). In the event of a hazardous event arising, persons in less protected locations will have a ***probability of escape*** to a more protected location. The ***protection factor*** and the ***probability of escape*** may vary between consequences.

Since the definitions of ***vulnerability*** do not appear to be precise, the term should be avoided.

1.3.4 Assessment Techniques

There are a wide range of ***hazard assessment*** (sometimes referred to as HAZAN) techniques. Most of these are mature systematic disciplines and some lend themselves primarily to the process industries, such as *loss prevention*.

Hazard analysis includes a systematic approach to hazard identification, using hazard identification techniques such as *HAZOP* which are primarily ***qualitative*** (but in the same way as the work done to date on landslips in Hong Kong and elsewhere, can include some ranking of ***consequence,***

frequency and/or *risk*), followed by assessment of the likelihood and severity of the hazards (which can involve either qualitative or quantitative analysis.

In Hong Kong the regulation of chemical risk is carried out by the Gas Standard Office of EMSD and the Air Policy Group of EPD. In accordance with the HK RGs, both require *Quantitative Risk Assessment* (QRA) of certain Potentially Hazardous Installations (PHIs) and may require risk assessments of Notifiable Gas Installations (NGIs).

EPD refer to the overall assessment as a hazard assessment whereas GasSO refer to the assessment as a QRA. GasSO have recently been requiring *Safety Cases* of PHIs such as LPG sites and oil terminal. A Safety Case includes a QRA but also includes descriptive sections on the storage systems, processes, safety managemnt system and engineering standards.

initiating event	a postulated occurrence capable of leading to the realisation of a hazard.
fault tree analysis	a method for representing the logical combinations of various system states which lead to a particular outcome (***top event***). BS 4778 specifies "an analysis to determine which fault modes of the subitems or external events, or combinations thereof, may result in a stated fault mode of the item, presented in the form of a fault tree".
top event	the selected outcome whose possible causes are analyzed in a ***fault tree***
event tree analysis	a method for illustrating the intermediate and final outcomes which may arise after the occurrence of a selected initial event
risk analysis	an imprecise term which infers the quantified calculation of probabilities and risks without taking any judgements about their relevance.
risk assessment	the qualitative evaluation of the likelihood of undesired events and the likelihood of harm or damage being caused together with the value judgements made concerning the significance of the results BS4778 and the Royal Society specify "the integrated analysis of the risks inherent in a product, system or plant and their significance in the appropriate context". The above IChemE definition appears to be more relevant here. BS4778 and the Royal Society further define ***risk quantification*** as "the estimation of a given risk by statistical and/or analytical modelling process".

residual risk	is the remaining risk after all proposed improvements to the system have been made
frequency	the number of occurrences per unit of time
probability	the number in a scale from 0 to 1 which expresses the likelihood that one event will succeed another Neither BS4778 nor the Royal Society Report provide any definition of ***frequency*** of ***probability***.
failure mode	the manner in which a slope or wall fails BS4778 defines a failure mechanism similarly.
common cause failure	the failure of more than one component, item or system due to the same cause
common mode failure	the failure of components in the same manner
hazard range	the relationship between distance from the source of hazard and detriment
F-N curve	a plot showing, for a specified hazard, the frequency of all events causing a stated degree of harm to N or more people against N (this is one measure of societal risk)
PLL	Potential Loss of Life is a second measure of societal risk also referred to as Rate of Death (RoD) and is the statistically expected number of fatalities (usually per year) from a given hazard

1.3.5 *Criteria*

criterion	is a standard of performance with which assessed performance may be compared
priority classification	if performance is unacceptable or could be improved then measures to do this can be prioritised, by for example their contribution to overall improvements in performance or their cost benefit (a ratio of the improvement which results from the measure and its cost).
two boundary criterion	is a compound criterion with a lower standard which must be achieved and an upper standard as an ultimate goal
societal risk criteria	criteria relating to the likelihood of a number of people suffering from a specified level of harm in a given population from the realisation of specified hazards

BS4778 and the Royal Society define ***risk criteria*** as "a qualitative and quantitative statement of the acceptable standard of risk with which the assessed risk needs to be compared".

major accident criterion	criterion (expressed as a frequency) for incidents falling within a defined category of consequences
individual risk criteria	criteria relating to the likelihood with which an individual may be expected to sustain a given level of harm from the realisation of specified hazards
average individual risk	is the average chance of any individual in a defined population sustaining a given level of harm from incidents which are considered to be limited to that population
peak individual risk	is the highest individual risk for any person in the exposed population
perceived risk	is that risk thought by an individual or group to be present in a given situation
land use planning	has an imprecise meaning in the context of hazard assessment, which implies that consideration is given to the location, layout, design features of any development in the vicinity of a hazard. Quantitative land use planning would include, for example, comparison against absolute criteria for individual developments and specification of maximum population density or usage.

In Hong Kong, the terms acceptable, ALARP and unacceptable are used to describe bands of levels of risk divided by the two boundary criteria. A Hazard Assessment assesses the risk posed by the system being considered to existing and potential future developments in the vicinity of the hazard to determine what, if any, actions need to be taken to reduce risks. For example, the Government Risk Guidelines (RGs) define acceptable risks as follows:

- *Individual Risk* (the risk to a single individual in a specific location): The maximum involuntary individual risk of death associated with accidents arising should not exceed a specified threshold; and

- *Societal Risk* (the risk to the population as a whole, independent of geographical location): The societal risk associated with a PHI should comply with the F-N diagram shown as by curves 5 and 6 in *Figure 1.2d*. The figure is a graphical representation of the cumulative frequency, F, of a number, N, or more fatalities resulting from potential accidents at a PHI plotted against N on a log-log scale. Three areas of risk are shown:

    - *Acceptable* where risks are so low that no action is necessary

- *Unacceptable* where risks are so high that they should usually be reduced regardless of the cost or the hazardous activity should not proceed

- *ALARP (As Low As Reasonably Practical)* where the risks associated with each probable hazardous event at the PHI should be reduced to a level 'as low as reasonably practical', usually measured as a trade off between the risk reduction afforded and the cost of that reduction. Risk mitigation measures may take the form of

  - engineered measures at the PHI
  - development (i.e. population) controls in the vicinity of the PHI

In the UK, the terms tolerable or negligable and intolerable are used. In the document "The Tolerability of Risk from Nuclear Power Stations", tolerability is defined as follows:

> "tolerability does not mean "acceptability". It refers to a willingness to live with a risk so as to secure certain benefits and in the confidence that it is being properly controlled. To tolerate a risk means that we do not regard it as negligible or something we might ignore, but rather as something we need to keep under review and reduce still further if we can. For a risk to be "acceptable" on the other hand means that for purposes of life or work, we are prepared to take it pretty well as it is.

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