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Quantitative Risk Assessment as Applied to Natural Terrain Landslide Hazard Management in a Mid-levels Catchment, Hong Kong

Ian Muir

Fugro Scott Wilson Joint Venture

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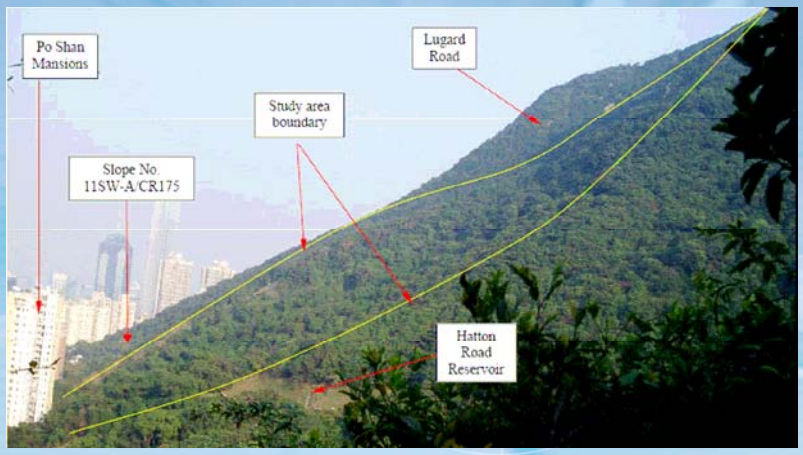
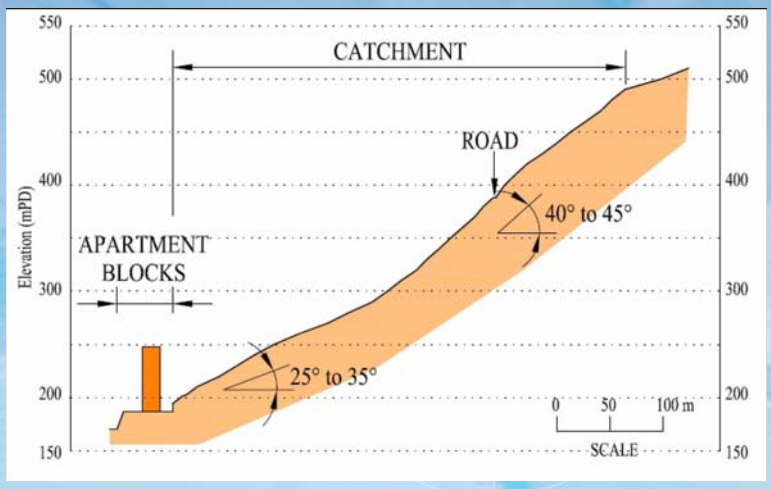
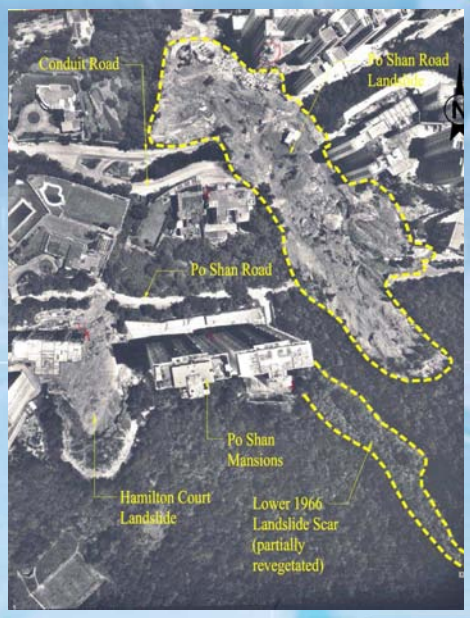
Po Shan Catchment



Section Through Catchment



1972 Po Shan Road Landslide



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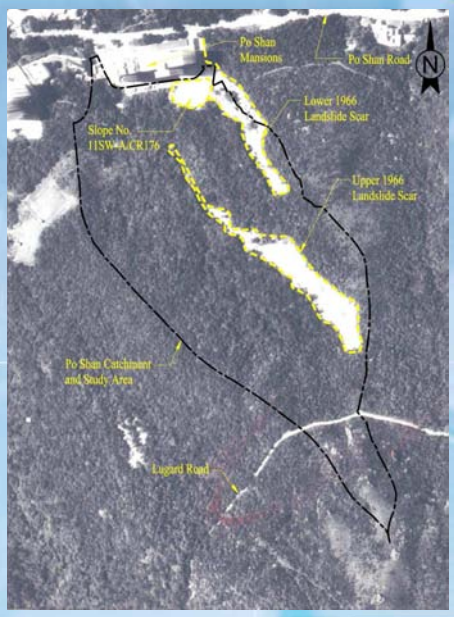
1966 Natural Terrain Landslides



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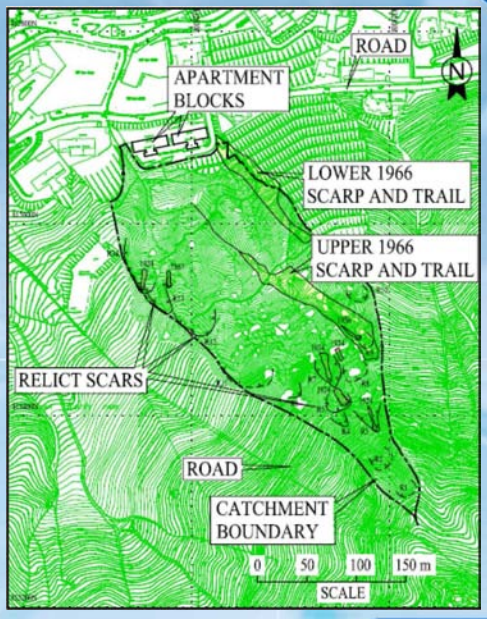
Historical Landslide Events



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Mid-levels Study

- Three rows of horizontal drains
- Max. length ~ 80m
- Surface drainage collection system

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Signs of Recent Movement

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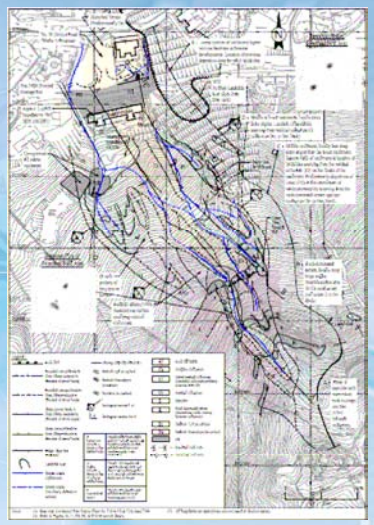
Geology

- **Colluvium (20m max.) overlying weathering profile of volcanic bedrock (30m max.) in lower portion of the site**
- **Saprolite and rock exposures predominate over upper portion of site above line of rock cliffs**
- **Two classes of colluvium: older deposit that has weathered insitu and younger deposit with higher proportion of coarse clasts and boulders**
- **Rockfall debris below rock cliffs**



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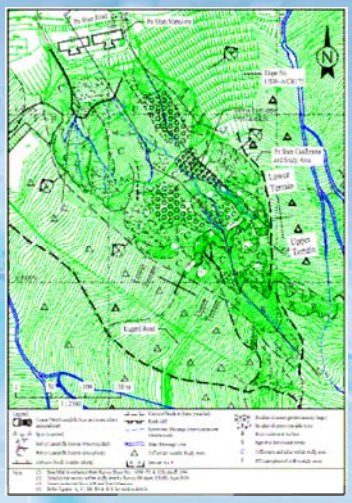
Geomorphology

- Catchment defined by divergent spur ridges
- Poorly defined drainage lines within
- Two lines of rock cliffs
- Elongate debris lobes below rock cliffs
- Relict landslide scars along flanks



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Quantitative Risk Assessment

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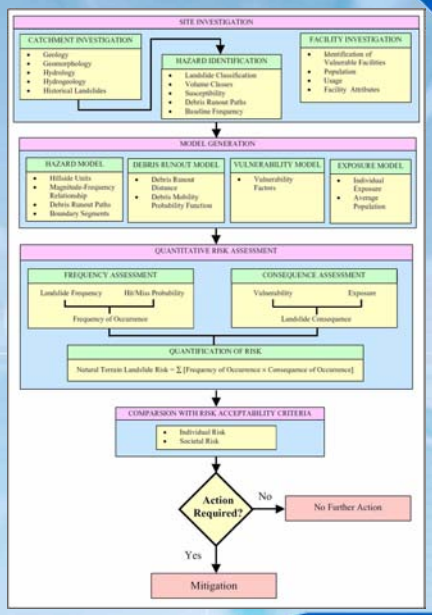
Overall QRA Methodology



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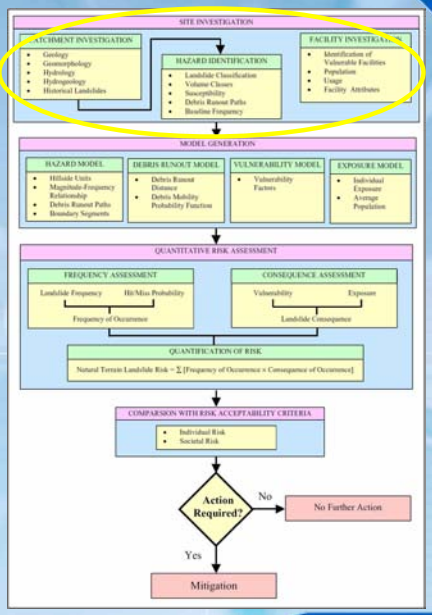
Site Investigation



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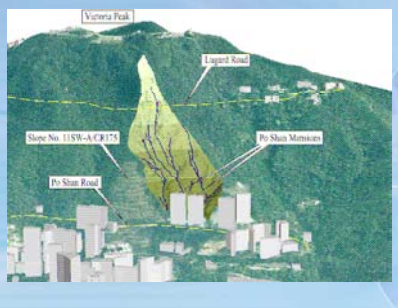
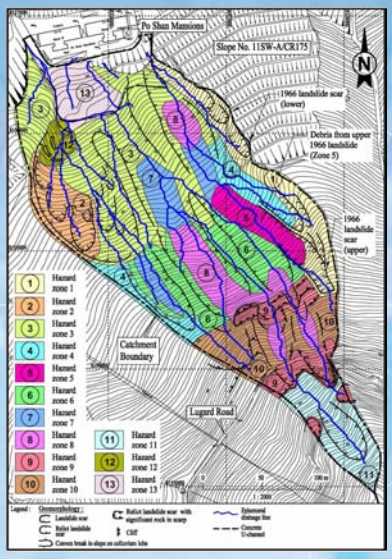
Hazard identification and hazard model

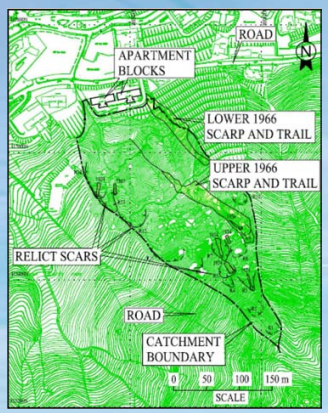


- Landslide Hazards
  - Type I: Shallow retrogression in old colluvium, E & W flanks
  - Type II: Shallow debris slides in upper portion of catchment
  - Type III: Rock slides on the rock cliffs
  - Type IV: Deap-seated failures in old colluvium & saprolite
- Types I & III dominant

Natural Terrain Landslide Hazard Zones



Landslide Volume Classes



Historical Landslides

Historical upper bound volume ~ 4000m³

Landslide Volume Class	Volume (m³)		Selected Mid-range Volume (m³)
	Lower Bound	Upper Bound	
H1	10	200	100
H2a	200	800	500
H2b	800	2000	1000
H3a	2000	8000	5000

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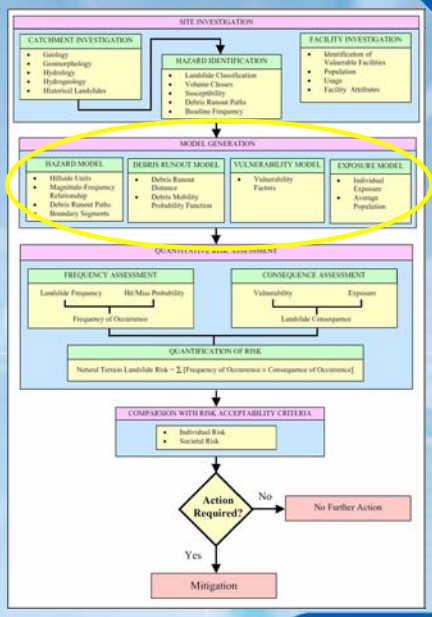
Model Generation



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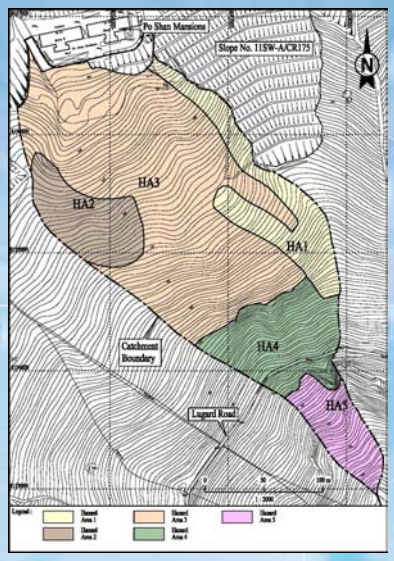
Natural Terrain Landslide Hazard Areas



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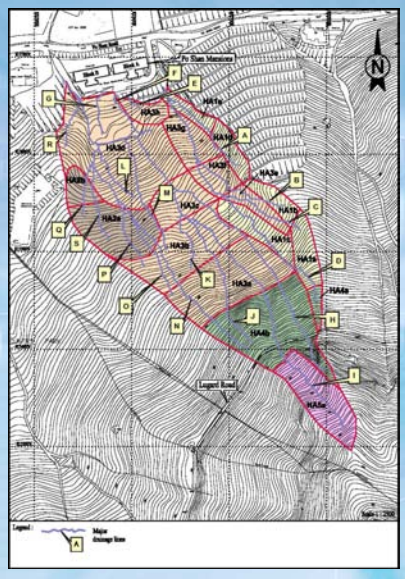
Hillside Units and Drainage Lines



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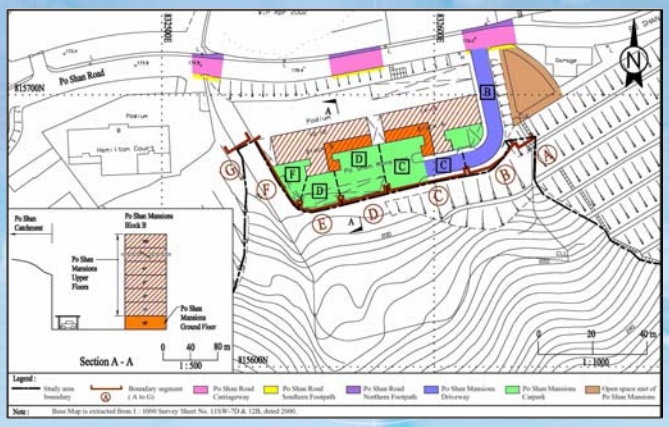
Boundary Segments and Vulnerable Facilities



Magnitude-Frequency Relationship

Hazard Area	Hillside Unit	Surface Area (m^2)	Relative Susceptibility	Distributed Natural Terrain Landslide Frequency (no./year)			
				H1	H2a	H2b	H3a
HA1	HA1a	2098	2	5.12E-03	0	1.54E-02	0
	HA1b	1265	1	1.55E-03	0	4.63E-03	0
	HA1c	2475	2	0	0	0	1.00E-03
	HA1d	1490	2	0	1.5E-02	0	0
	HA1e	996	1	0	5.01E-03	0	0
HA2	HA2a	4904	1	5.33E-02	6.39E-03	1.06E-03	0
	HA2b	1236	1	1.34E-02	1.61E-03	2.68E-04	0
HA3	HA3a	7868	4	1.00E-02	7.64E-04	7.64E-05	0
	HA3b	6109	2	3.89E-03	2.97E-04	2.97E-05	0
	HA3c	2570	1	8.19E-04	6.24E-05	6.24E-06	0
	HA3d	11683	1	3.72E-03	2.84E-04	2.84E-05	0
	HA3e	1326	2	8.45E-04	6.44E-05	6.44E-06	0
	HA3f	1618	1	5.16E-04	3.93E-05	3.93E-06	0
	HA3g	2514	1	8.10E-04	6.10E-05	6.10E-06	0
	HA3h	1161	1	3.70E-04	2.82E-05	2.82E-06	0
HA4	HA4a	596	1	7.07E-04	1.31E-04	2.07E-05	5.32E-06
	HA4b	10610	1	1.26E-02	2.34E-03	3.69E-04	9.47E-05
HA5	HA5a	4792	1	2.13E-03	4.25E-04	5.00E-05	0

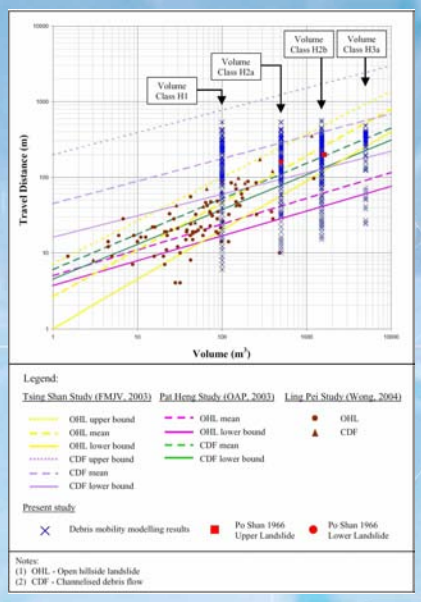
Debris Mobility Modelling (DMM)

- GEO-DAN (after Hungr, 1995)
- Assumed 'Voellmy Fluid' model to describe basal flow resistance
  - Apparent Friction Angle, ϕ
  - Turbulence Coefficient, ξ
- Range of debris mobility estimated by:
  - Runout distance for 7 sets of basal flow resistance parameters
  - Block probability function for parameter sets

Parameter Sets and Probability Function

Parameter Set	Apparent Friction Angle, ϕ (°)	Turbulence Coefficient, ξ (m/s^2)	Probability Distribution of Debris Mobility for Landslide Volume Class			
			H1	H2a	H2b	H3a
1	8	500	0	0	0	2%
2	11	500	0	0	2%	5%
3	15	1000	0	3%	5%	13%
4	20	1000	3%	7%	13%	30%
5	25	5000	7%	20%	35%	30%
6	30	5000	45%	35%	35%	10%
7	35	∞	45%	35%	10%	10%

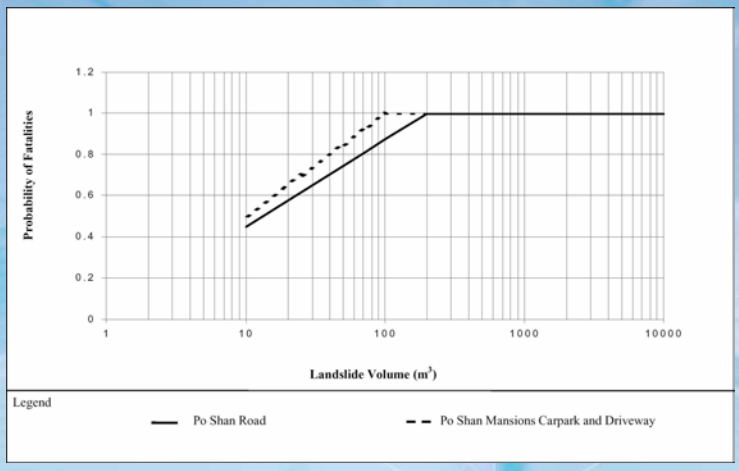
DMM Results



Vulnerability Model

- **Overall Vulnerability Factor = Product of individual attribute-specific factors**
- **<u>Debris-related attributes</u>**
  - **Volume**
  - **Mobility**
- **<u>Facility-related attributes</u>**
  - **Vehicle Protection**
  - **Building Protection**

Vehicle Protection Factor, V_P



Exposure Model

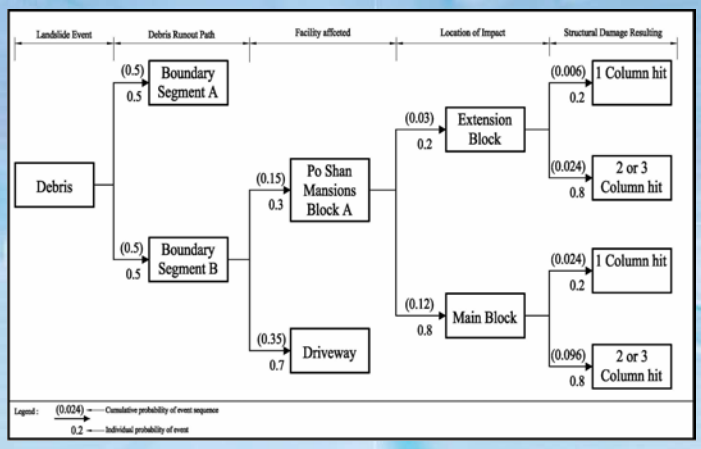
- **For each Vulnerable Facility:**
  - **Individual Exposure (Most Vulnerable Individual)**
  - **Average Populations**

Individual Exposure and Average Populations

Vulnerable Facility		Individual Exposure	Average Population
Po Shan Rd Nth Footpath (Segment 1)		1.8E-05	1.1E-02
Po Shan Rd Nth Footpath (Segment 2)		2.1E-04	1.3E-02
Po Shan Rd Nth Footpath (Segment 3)		2.5E-04	1.5E-02
Po Shan Rd Carriageway (Segment 1)		3.6E-05	2.6E-02
Po Shan Rd Carriageway (Segment 2)		4.4E-05	3.1E-02
Po Shan Rd Carriageway (Segment 3)		2.5E-04	3.6E-01
Po Shan Rd Nth Footpath (Segment 1)		1.8E-05	1.1E-02
Po Shan Rd Nth Footpath (Segment 2)		2.1E-04	1.3E-02
Po Shan Rd Nth Footpath (Segment 3)		2.5E-05	1.5E-02
Open Space East of Po Shan Mansions		6.9E-05	3.0E-02
Po Shan Mansions Driveway		2.4E-04	8.3E-02
Po Shan Mansions Carpark (Pedestrians)	Segment B	1.3E-04	9.3E-02
	Segment C	3.4E-04	3.4E-01
	Segment D	2.7E-04	1.9E-01
	Segment E	3.2E-04	2.2E-01
	Segment F	2.2E-04	1.5E-01
Po Shan Mansions Carpark (Veh. Pass.)	Segment B	1.3E-04	2.0E-02
	Segment C	1.8E-04	1.7E-01
	Segment D	1.2E-03	1.7E-01
	Segment E	1.8E-04	6.1E-02
	Segment F	1.8E-04	6.1E-02
Po Shan Mansions Ground Floor		3.2E-01	2.1E+00
Po Shan Mansions Upper Floors		7.5E-01	1.2E+02

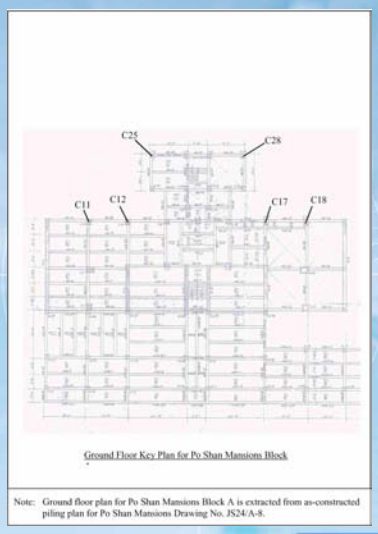
Building Collapse Scenario

- **Event-tree**



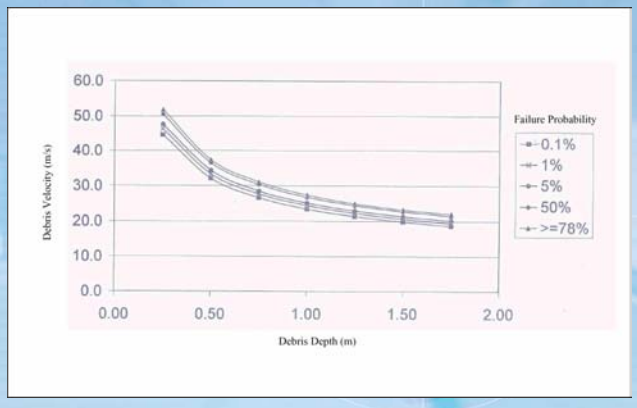
Building Collapse Scenario

- **Structural Analysis**



Building Collapse Scenario

- **Probability of Collapse**



Building Collapse Scenario

- DMM Results
- Floor Area Affected
- Vulnerability
- Individual Exposure & Average Populations

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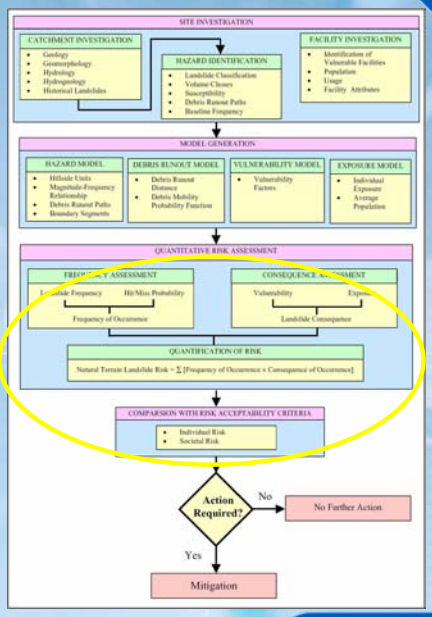
Risk Quantification & Acceptability Criteria



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Quantification of Risk

Risk

=

Σ(Frequency of Occurrence x Consequence of Occurrence)

- **Individual Risk**
- **Societal Risk**

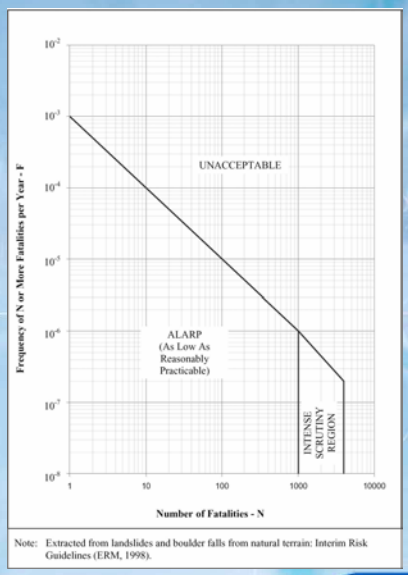
Individual Risk

- **Personal Individual Risk**
- **Σ(Frequency of Occurrence x Vulnerability x Individual Exposure)**
- **Summation for:**
  - **All volume classes**
  - **All hillside units**
  - **Individual facilities**
- **Acceptability Criterion: < 10^{-4}**

Societal Risk

- **Potential Loss of Life (PLL)**
- **Σ(Frequency of Occurrence x Vulnerability x Average Population)**
- **Summation for:**
  - **All Volume Classes**
  - **All hillside units**
  - **All facilities**
- **Acceptability criteria applied to generated F-N pairs and based on ALARP principle**

Societal Risk Acceptability Criteria



Note: Extracted from landslides and boulder falls from natural terrain: Interim Risk Guidelines (ERM, 1998).

Individual Risk at Vulnerable Facilities (Current Condition)

Vulnerable Facility	Personal Individual Risk
Po Shan Rd Northern Footpath	1.2E-07
Po Shan Rd Carriageway	1.7E-07
Po Shan Rd Southern Footpath	3.4E-07
Open Space East of Po Shan Mansions	3.6E-07
Po Shan Mansions Driveway	1.6E-06
Po Shan Mansions Carpark	2.2E-06
Po Shan Mansions Ground Floor	2.1E-04
Po Shan Mansions Upper Floors	8.6E-07

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Societal Risk at Vulnerable Facilities (Current Condition)

Vulnerable Facility	PLL
Po Shan Rd Northern Footpath	7.2E-06
Po Shan Rd Carriageway	2.4E-04
Po Shan Rd Southern Footpath	2.0E-05
Open Space East of Po Shan Mansions	1.6E-04
Po Shan Mansions Driveway	5.5E-04
Po Shan Mansions Carpark (Pedestrians)	9.2E-04
Po Shan Mansions Carpark (Veh. Pass.)	4.5E-04
Po Shan Mansions Ground Floor	1.4E-03
Po Shan Mansions Upper Floors	1.4E-04
Total	3.9E-03

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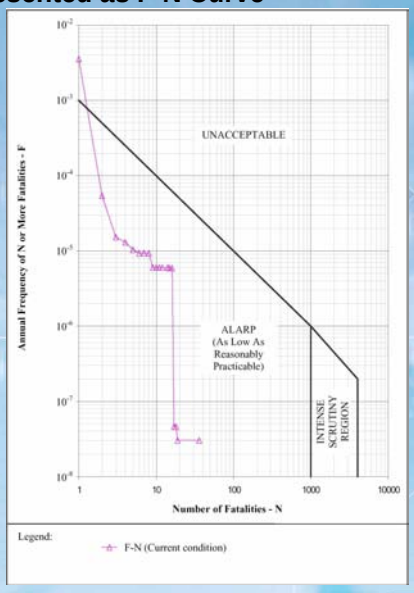
Societal Risk presented as F-N Curve



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PLL Attributable to Hazard Areas (Current Condition)

Hazard Area	PLL	%
HA1	3.6E-03	92.0
HA2	6.2E-05	1.6
HA3	1.1E-04	2.7
HA4	1.3E-04	3.4
HA5	7.7E-06	0.2
Total	3.9E-03	100

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PLL Attributable to Volume Classes (Current Condition)

Volume Class	Volume Range (m^3)	PLL	%
H1	10 – 200	6.5E-05	1.7
H2a	200 – 800	6.1E-04	15.8
H2b	800 – 2000	2.4E-03	62.8
H3a	2000 - 8000	7.7E-04	19.8
	Total	3.9E-03	100

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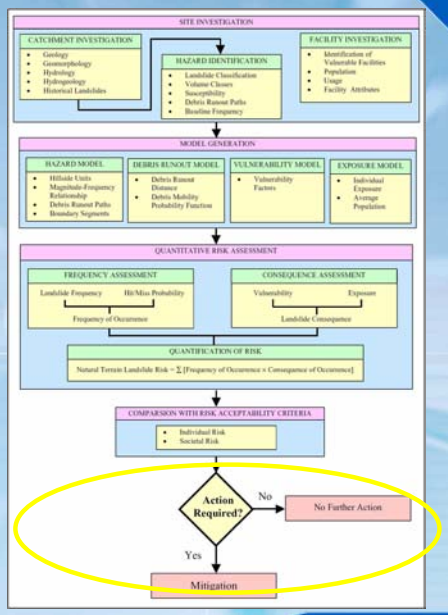
Mitigation



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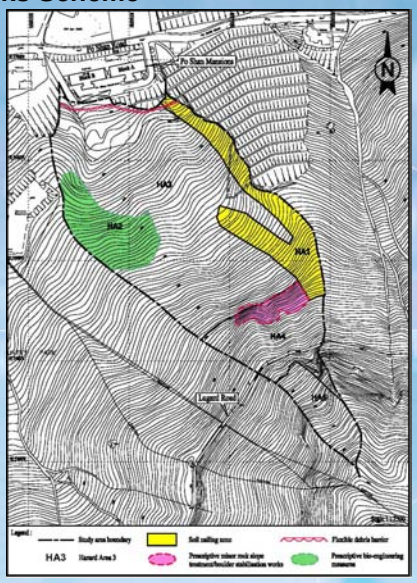
Maximum Justifiable Expenditure

- MJE = (PLL x Design Life x 'Value of a Life' x Aversion Factor)
  - Design Life = 120 years
  - Value of Life = HK$24 million to 33 million
  - Aversion Factor = unity
- => MJE = HK$11 million to 15 million

Mitigation Strategy

- Combination of Preventive and Protective Measures
- Preventive Works comprising:
  - Localised soil nailing within Hazard Area 1
- Prescriptive measures comprising:
  - Flexible debris barrier along northern catchment boundary
  - Surface drainage improvement
  - Minor rock slope/boulder stabilisation at rock cliffs
  - Bio-engineering measures in Hazard Area HA2
- Estimated cost = HK$6 million < MJE

Mitigation Works Scheme



Residual Risk

- Reduce frequency of occurrence of natural terrain landslides in all volume classes in Hazard Area HA1 by factor of 100.
  - Individual Risk
  - Societal Risk

Individual Risk (Following Mitigation)

Vulnerable Facility	Personal Individual Risk
Po Shan Rd Northern Footpath	1.0E-08
Po Shan Rd Carriageway	5.0E-09
Po Shan Rd Southern Footpath	2.9E-08
Open Space East of Po Shan Mansions	7.9E-08
Po Shan Mansions Driveway	2.5E-07
Po Shan Mansions Carpark	5.0E-08
Po Shan Mansions Ground Floor	2.2E-05
Po Shan Mansions Upper Floors	2.9E-08

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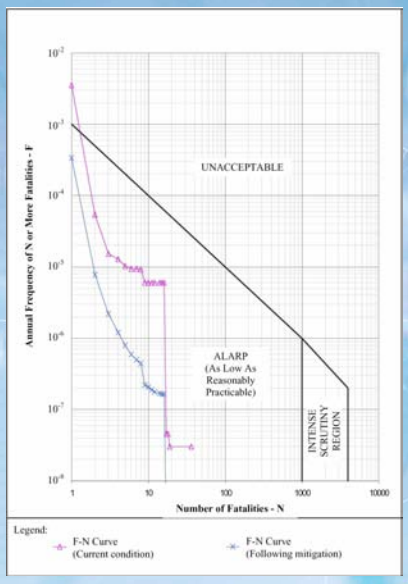
Societal Risk (Following Mitigation)



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