

THE 11TH LUMB LECTURE

Bridging the Gap between Theoretical and Actual Slope Performance

Ir Prof. WONG Hok-ning

6:30 P.M. DECEMBER 3, 2021 (FRIDAY)

RAYSON HUANG THEATRE, THE UNIVERSITY OF HONG KONG



Department of Civil Engineering
The University of Hong Kong

HKIE Geotechnical Division
The Hong Kong Institution of Engineers

$$\frac{\partial x}{\partial z} = \frac{1}{\sqrt{4bt}}; \quad \frac{\partial x}{\partial t} = \frac{z}{\sqrt{4D}} \left(-\frac{1}{2} t^{-\frac{3}{2}}\right)$$

$$= -\frac{x}{2t}$$

$$\frac{\partial \theta}{\partial t} = \frac{d\theta}{dx} \cdot \frac{\partial x}{\partial t} = -\frac{x}{2t} \frac{d\theta}{dx}$$


$$\frac{\partial \theta}{\partial z} = \frac{d\theta}{dx} \left(\frac{\partial x}{\partial z}\right) = \frac{1}{\sqrt{4bt}} \frac{d\theta}{dx}$$

$$\frac{\partial^2 \theta}{\partial z^2} = \frac{1}{\sqrt{4bt}} \left\{ \frac{1}{\sqrt{4bt}} \frac{d^2 \theta}{dx^2} \right\} = \frac{1}{4bt} \frac{d^2 \theta}{dx^2}$$

$$-\frac{x}{2t} \frac{d\theta}{dx} = \frac{1}{4bt} \frac{d^2 \theta}{dx^2} = 0$$

solve $\Rightarrow \frac{d^2 \theta}{dx^2} + 2x \frac{d\theta}{dx} = 0$

Let $y = \frac{d\theta}{dx}$



OUR PROFESSOR

*Unsaturated seepage flow taught by Prof. Lumb in 1982
 (HN Wong's notes)*

Slope Failures in Hong Kong ← Lumb (1975)

P. Lumb

Department of Civil Engineering, The University of Hong Kong

Summary: The recurrence of slope failures in residual soils of Hong Kong is analysed for the period 1950 to 1973, and various factors contributing to the instability are described. It is postulated that the prime cause of the failures is direct infiltration of rain water into the surficial zones of the slopes, producing a loss of effective cohesion following the saturation of the soil. Prevention of slips implies protection against excessive infiltration.

“the prime cause of the failures [1950 to 1973] is **direct infiltration** of rain water into the **surficial zones** of the slopes ...”

“Prevention of slips implies **protection against excessive infiltration**”

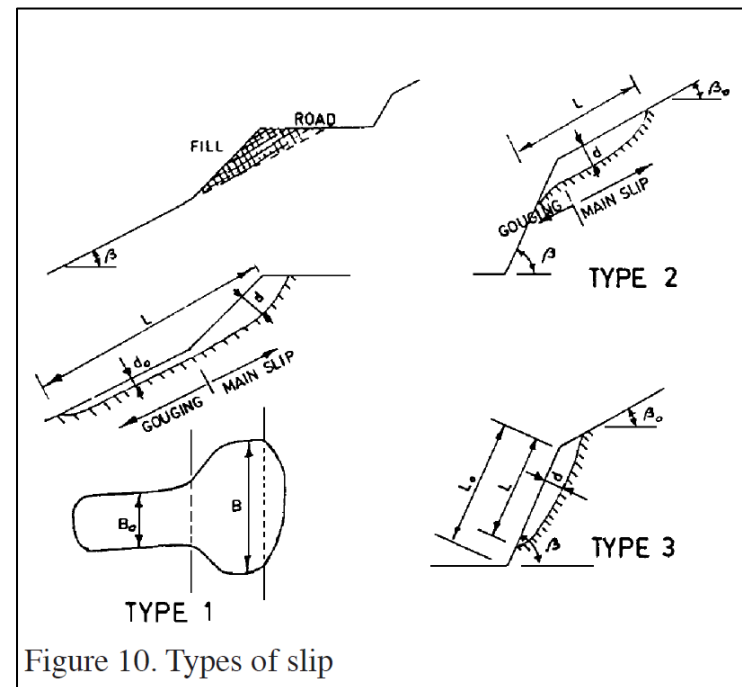


Figure 10. Types of slip

Bridging the Gap between Theoretical and Actual Slope Performance

(1) Is there a gap ?



“Un-engineered” slope



1977



“Engineered” slope

Failure ?



香港斜坡治理領先世界秘訣

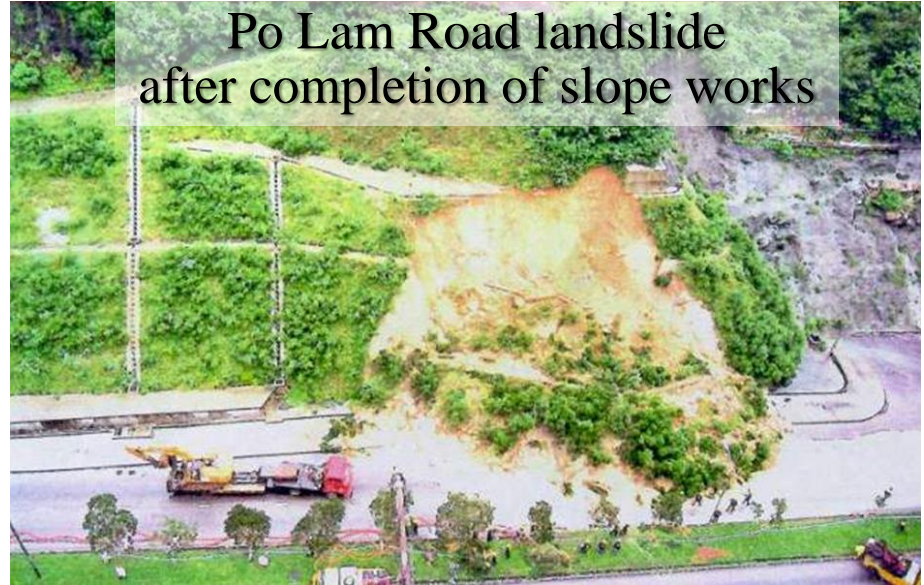
香港市民安全與發展息息相關。為解決土力工程處專門治理斜坡，花一億元重金採集紀錄，探尋最佳方案。創製有系統治理，加強預防及教育，務求與世界領先城市並駕齊驅，成為香港的又一個驕傲。

香港土力工程處為確保斜坡安全，採取多項措施，包括加強巡查、改善排水系統、加強預防及教育等。此外，土力工程處亦積極與市民合作，提高公眾對斜坡安全的意識。這些措施不僅確保了市民的安全，也為香港的發展提供了堅實的保障。

Leading edge of Hong Kong Slope Safety

**Doing well, but
not good enough**

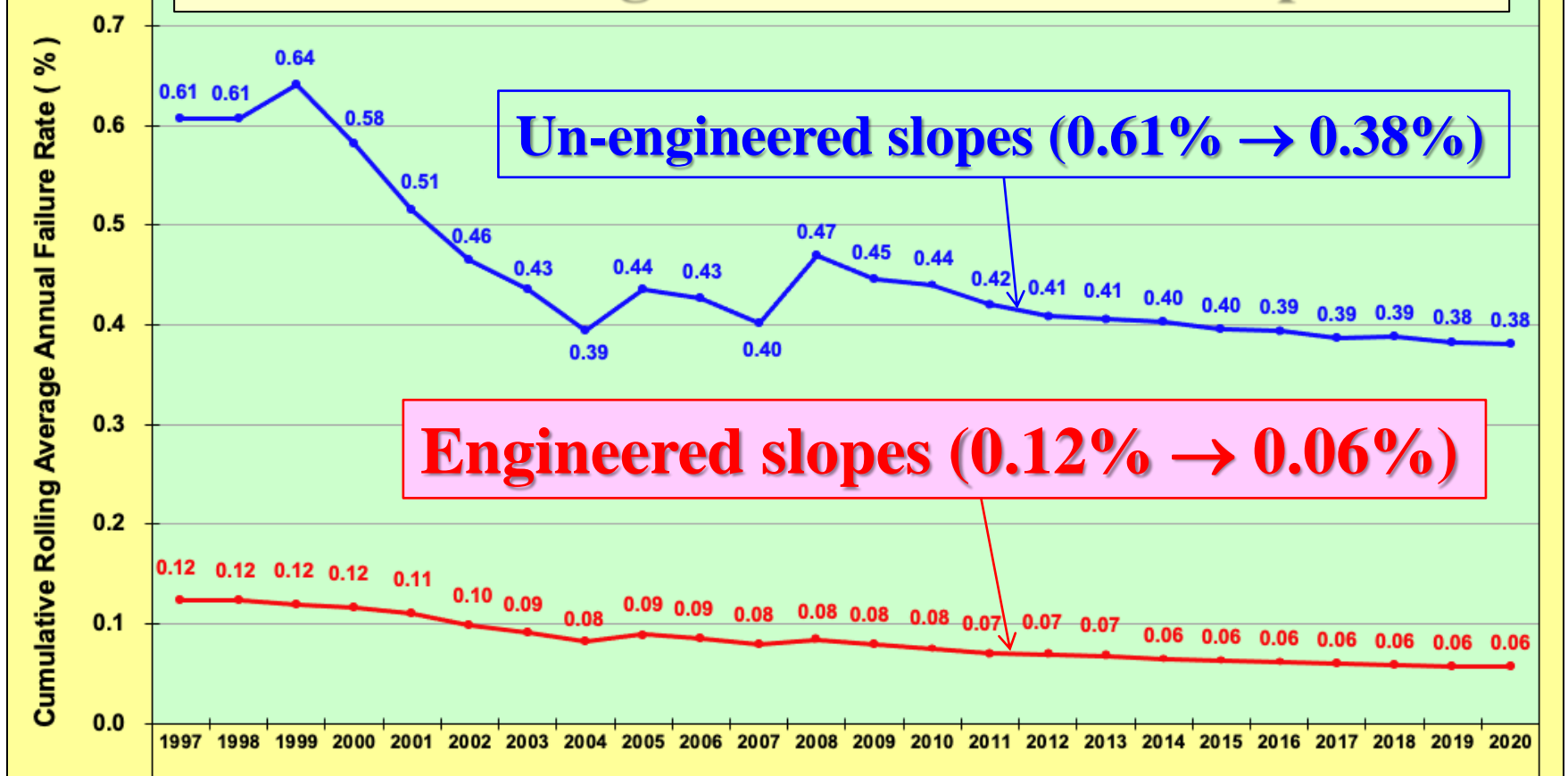
Po Lam Road landslide
after completion of slope works



Ching Cheung Road landslide
after upgrading works








Cumulative Rolling Average Annual Failure Rate of Registered Man-made Slopes



1997 → 2020
 Annual Failure Rate = 0.06% (**326** landslides in **24** years)

Annual Failure Rate (Permanent Structures in Hong Kong)

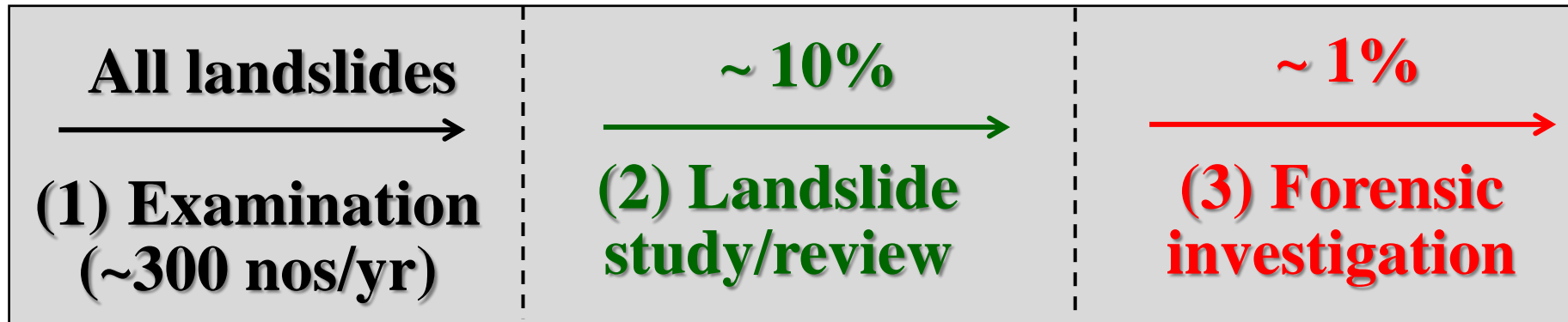
Type	Unengineered	Engineered
Man-made slope	<p>~1/200</p> 	<p>~1/2000[#]</p> 
Retaining Wall	<p>~1/500</p> 	<p>Negligible</p> 
Building	<p><i>not known</i></p>	<p>Negligible</p> 

~ 6% of the slopes would fail at least once in notional 120-year design life

Bridging the Gap between Theoretical and Actual Slope Performance

(2) Where come the gap ?

Systematic Landslide Investigation (1997 onwards)



1994 Kwun Lung Lau Landslide

Systematic
landslide investigation
as part of the
Landslip Preventive Measure
(LPM) Programme

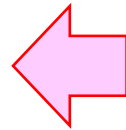


Morgenstern (1995 & 2000)

Model

Parameter

Human



**Failure mechanism
differs from
the model
analyzed in design**

Wash-out failures

Concentrated surface water flow in urban environment



Environmental Factors in Triggering Slope Failures

S. W. C. Au & R. Y. C. Suen

Geotechnical Engineering Office, Civil Engineering Department, Hong Kong



(i) Topographic

e.g. concentrated discharge at low point



(i) Topographic e.g. road bend



Roads flow like river in heavy rain



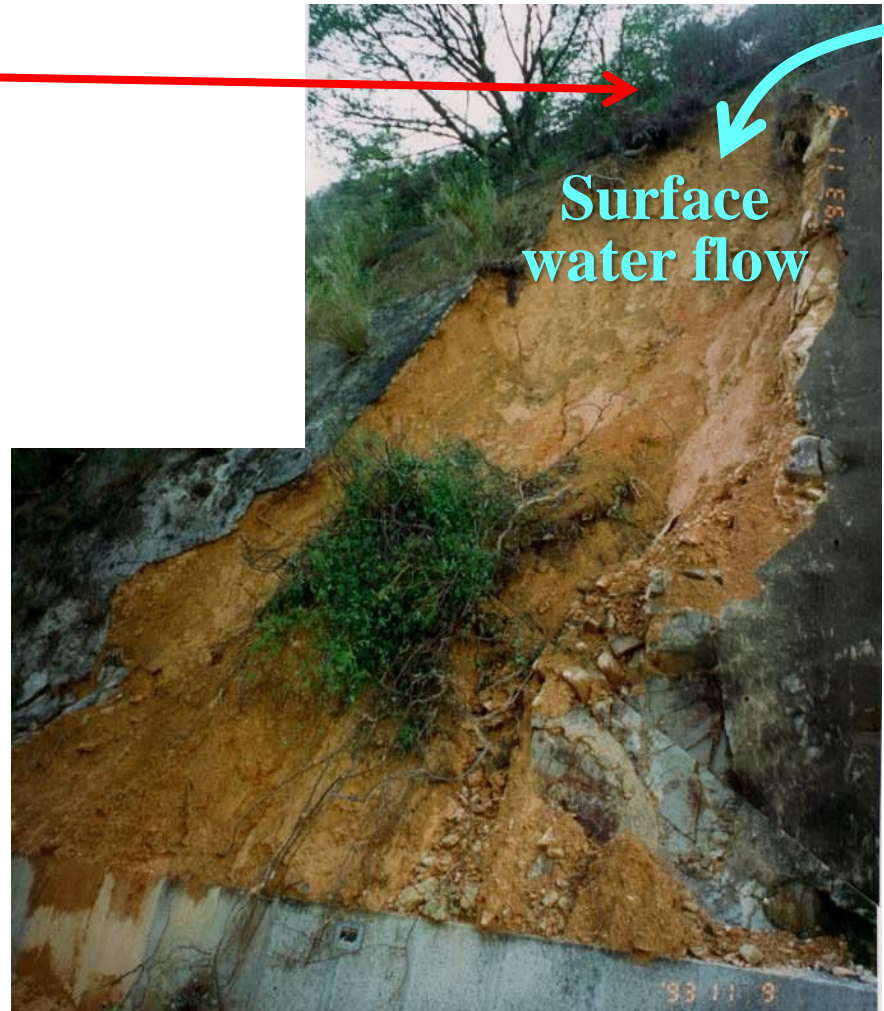
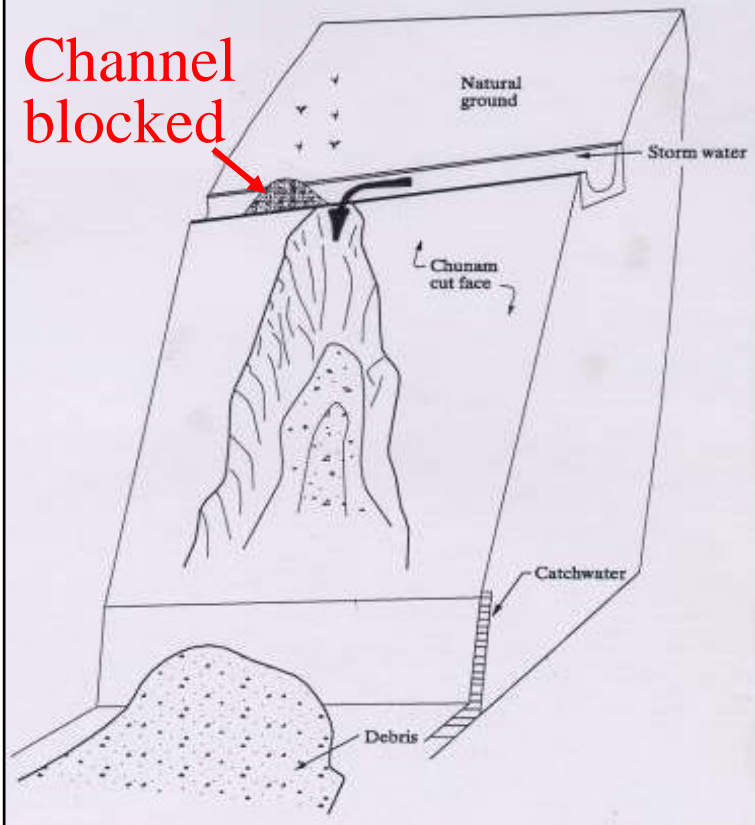
Typhoon Lionrock Oct 2021

(ii) Blockage

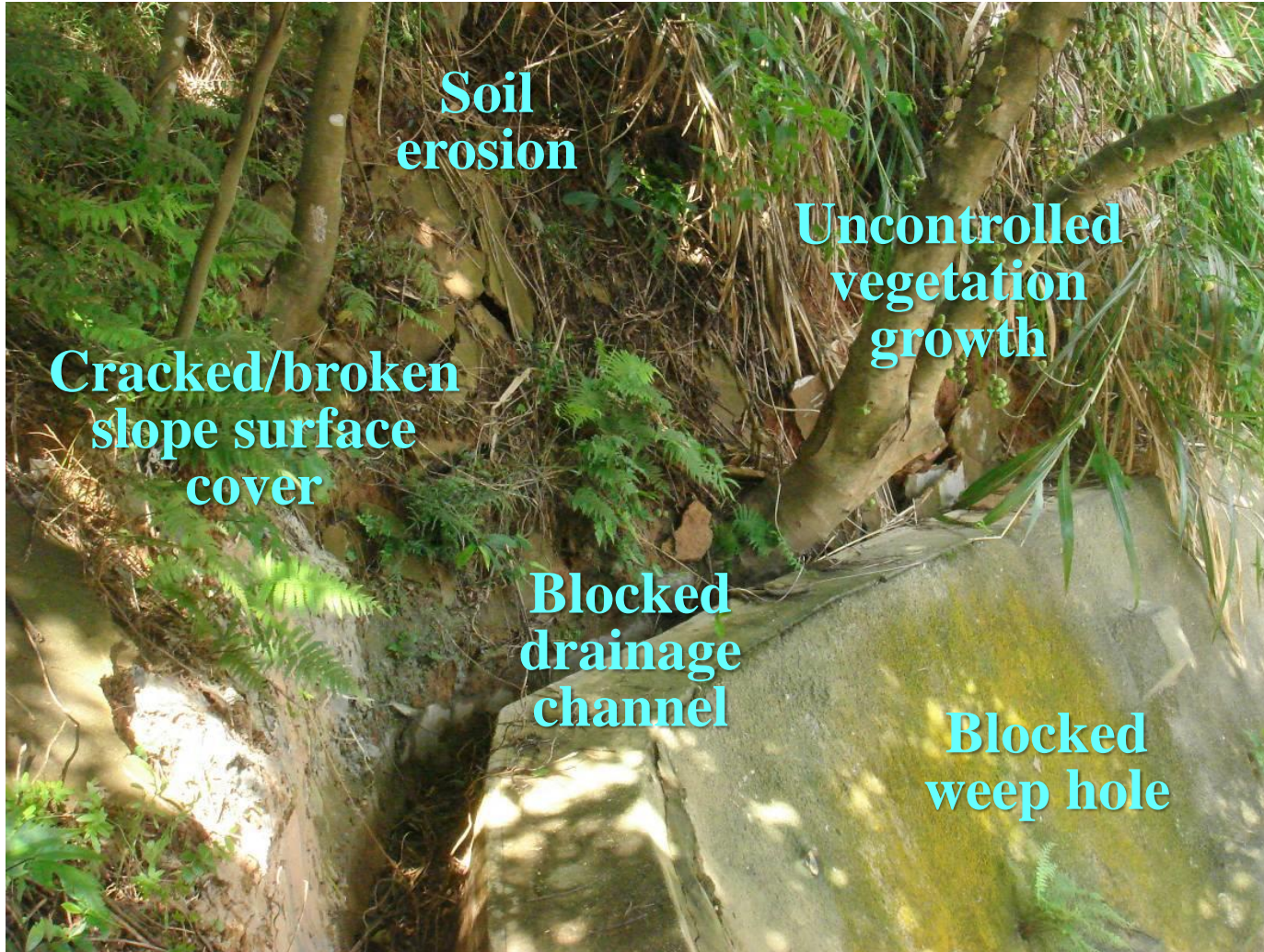
e.g. surface drainage channel

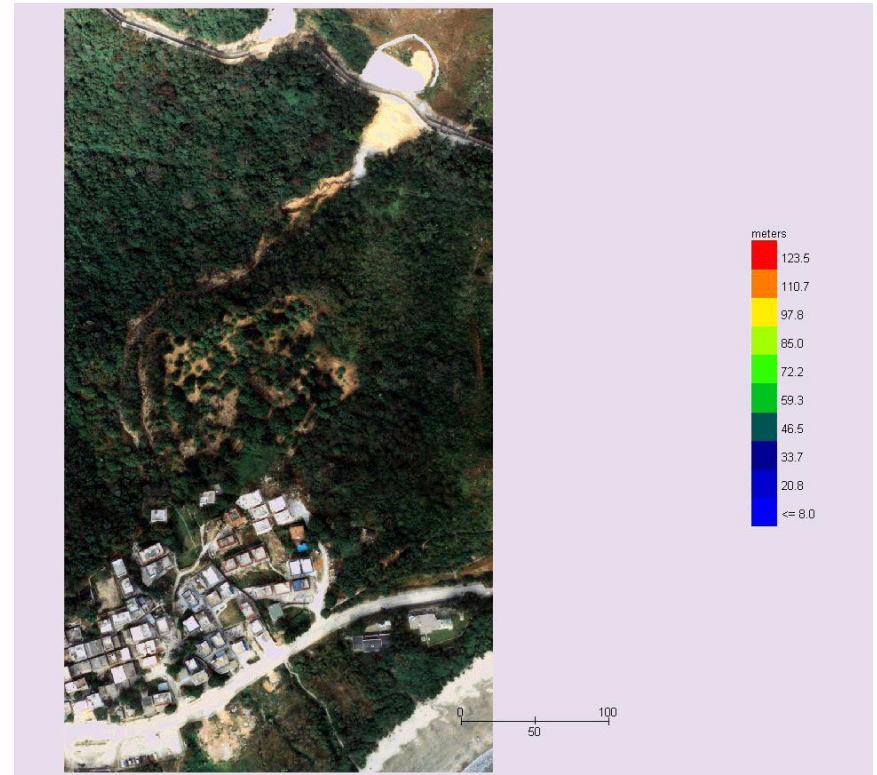
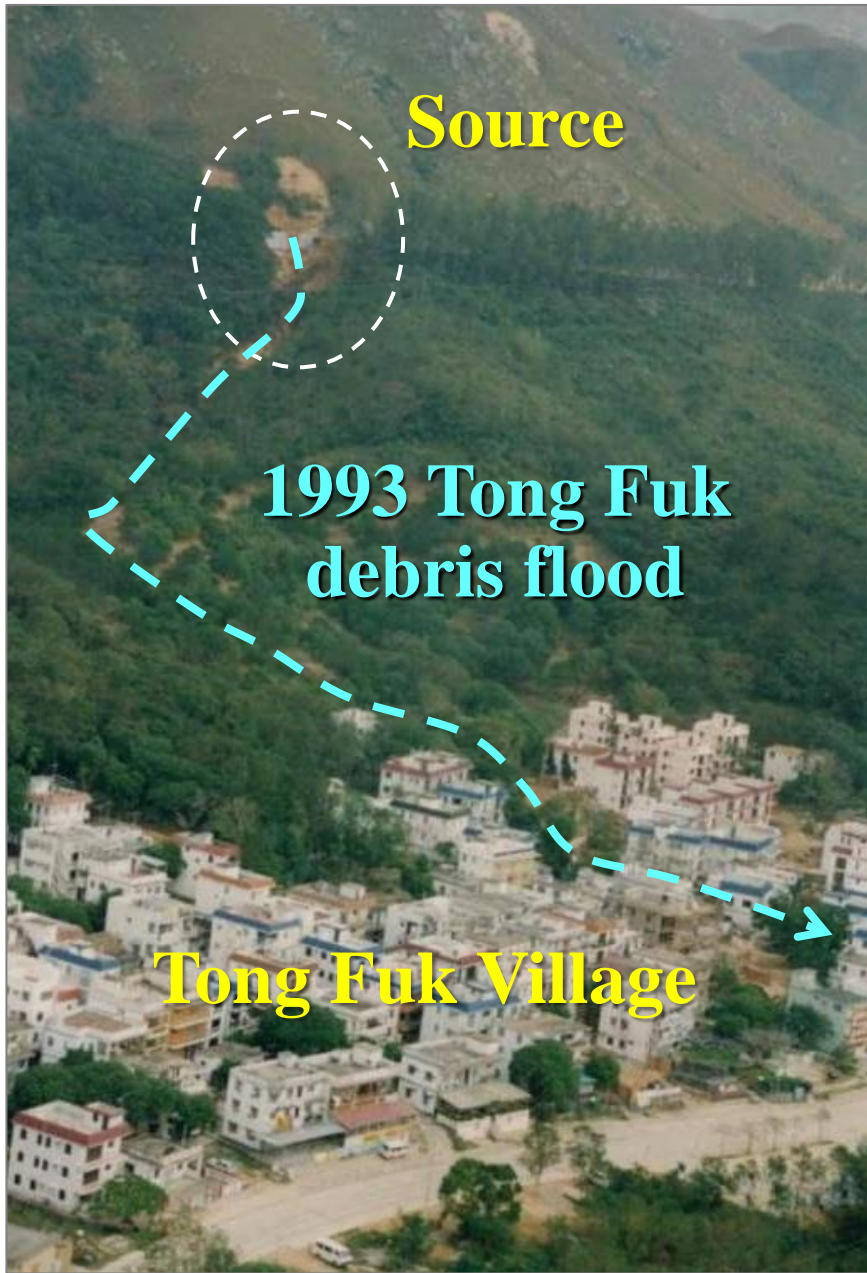
Blockage by debris and unplanned vegetation

Channel blocked



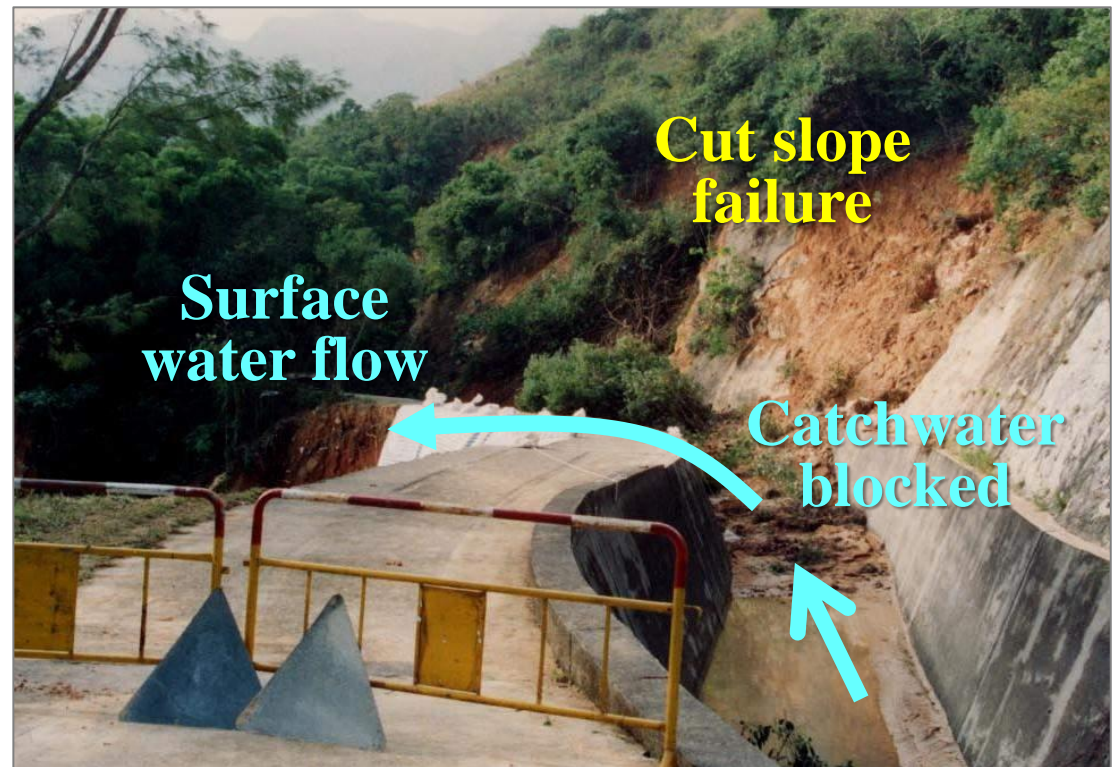
Lack of slope maintenance





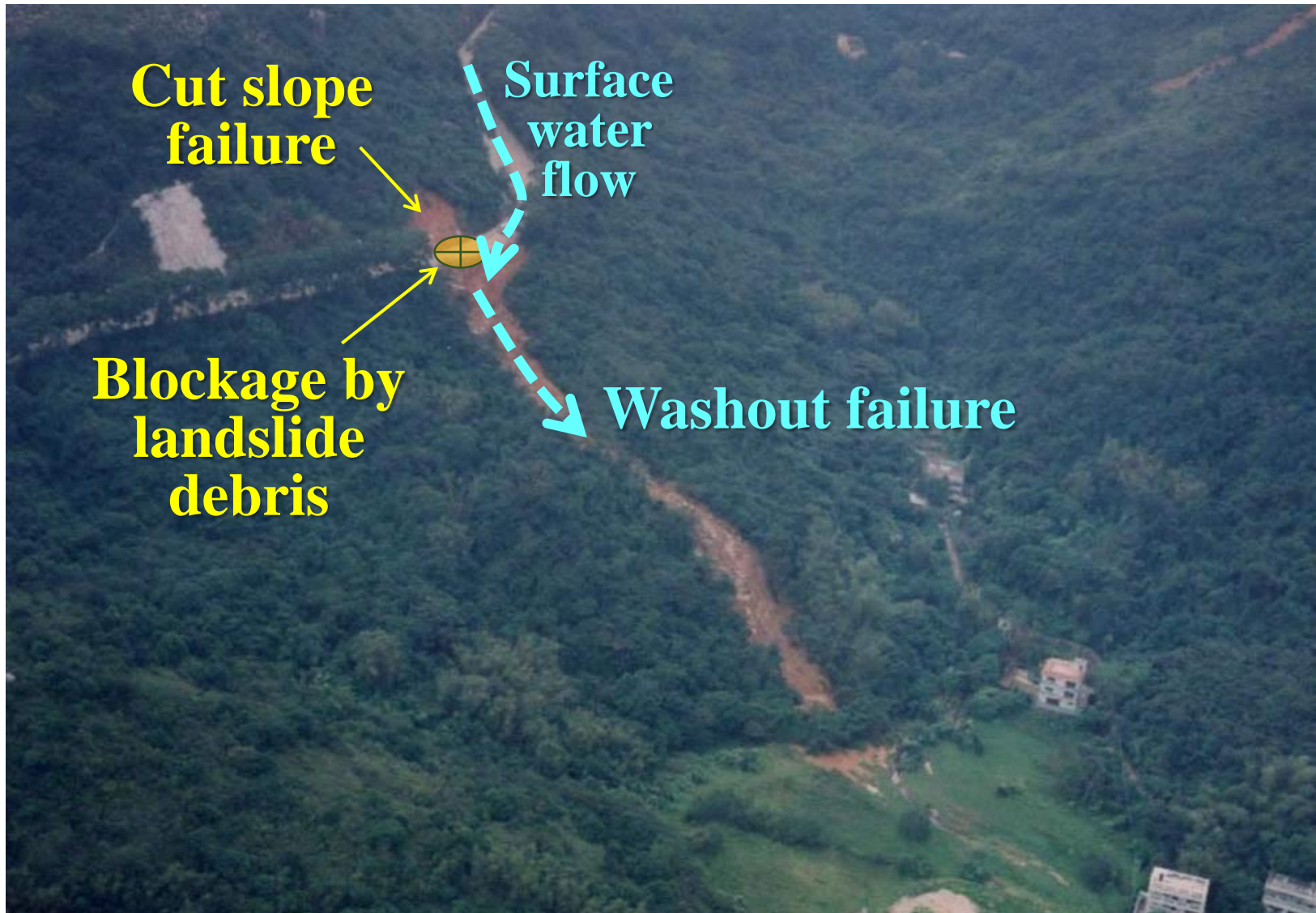
(ii) Blockage

e.g. catchwater blocked by landslide debris



(ii) Blockage

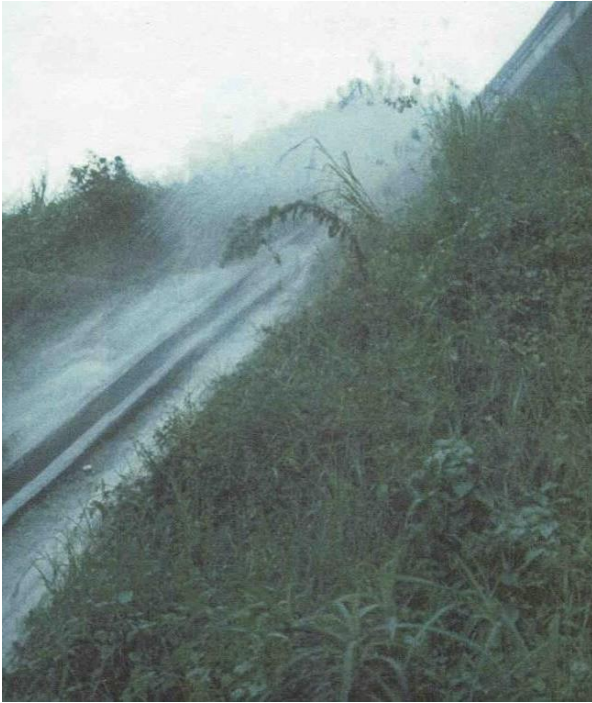
e.g. road blocked by landslide debris



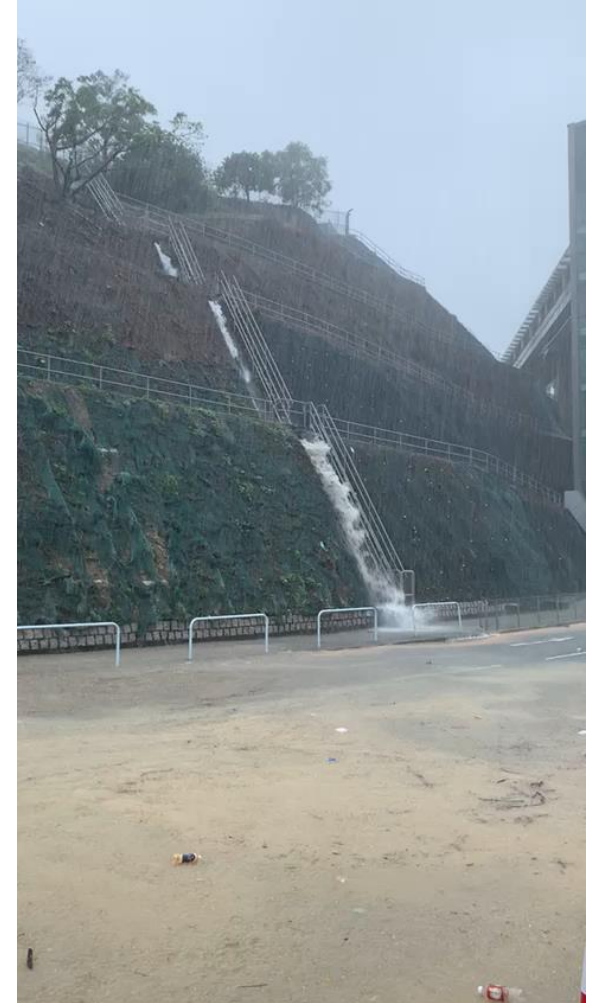
Fill slope + eroded to weathered rock



(iii) Deficient drainage alignment and detailing



(HN Wong 8.10.2021)



(Raymond Cheung 8.10.2021)

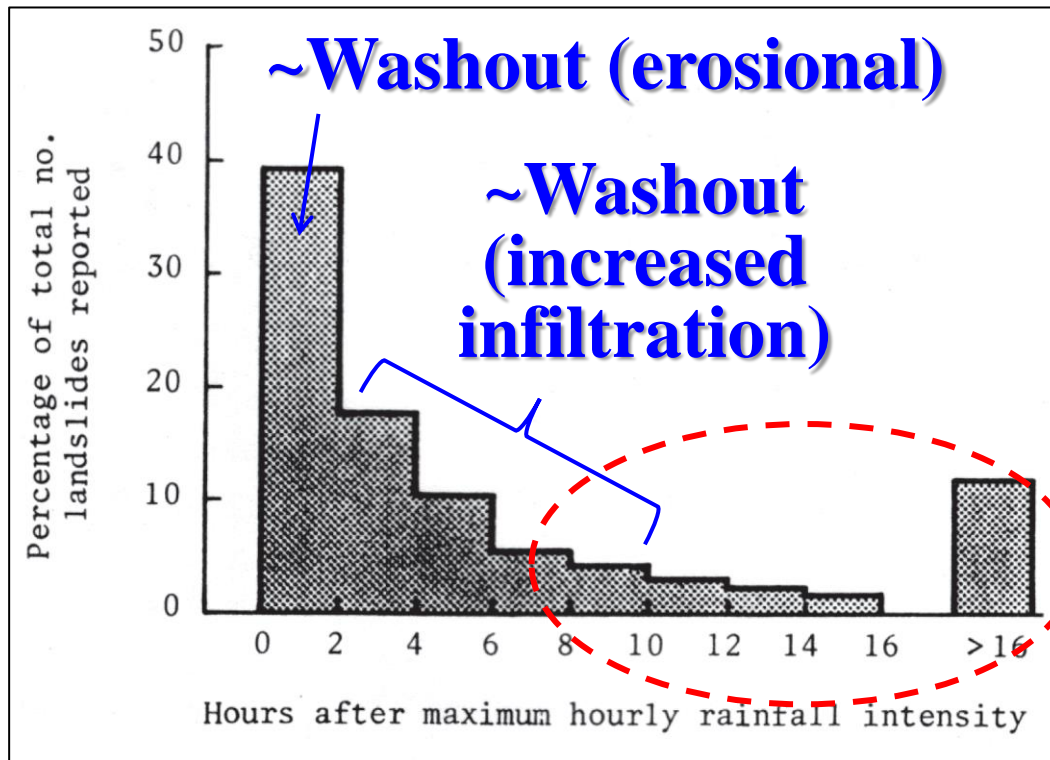
Relationship between Rainfall and Landslides in Hong Kong

E. W. Brand, J. Premchitt & H. B. Phillipson

Geotechnical Control Office, Engineering Development Department, Hong Kong

**Brand et al
(1984)**

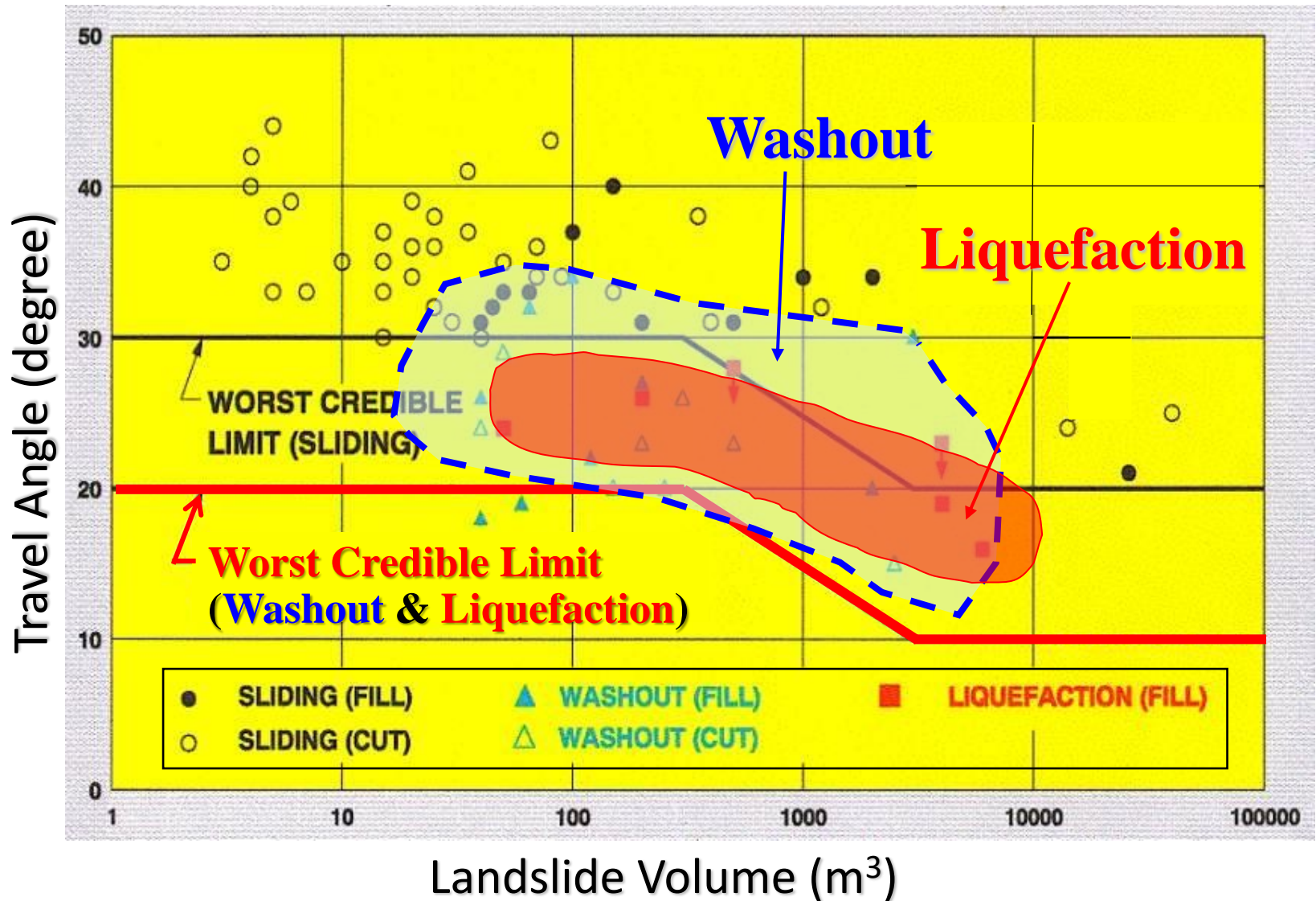
“... landslides in Hong Kong are heavily dependent on the magnitude of the short duration rainfall intensity, with a threshold value of about 70 mm/hour”



Soil infiltration rate
 $< 5 \times 10^{-6}$ m/s
 $= 18$ mm/hr $\ll 70$ mm/hr

Thickness of wetted zone
 < 0.5 m in 2 hrs

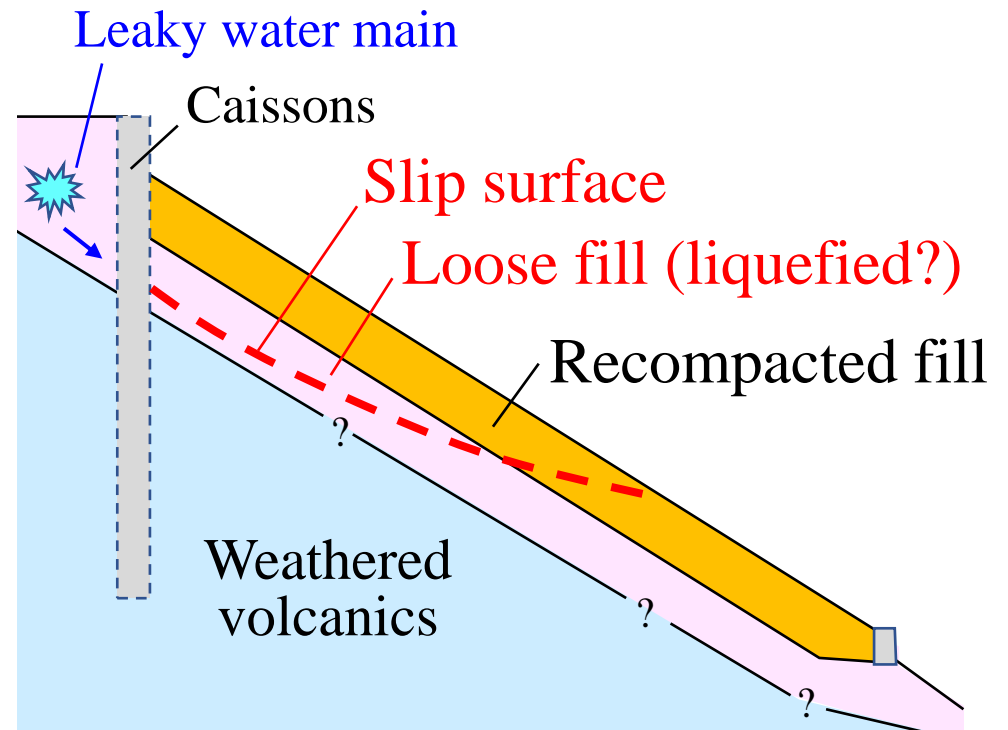
“Genuine” landslides



Nov 2021 Peak Road

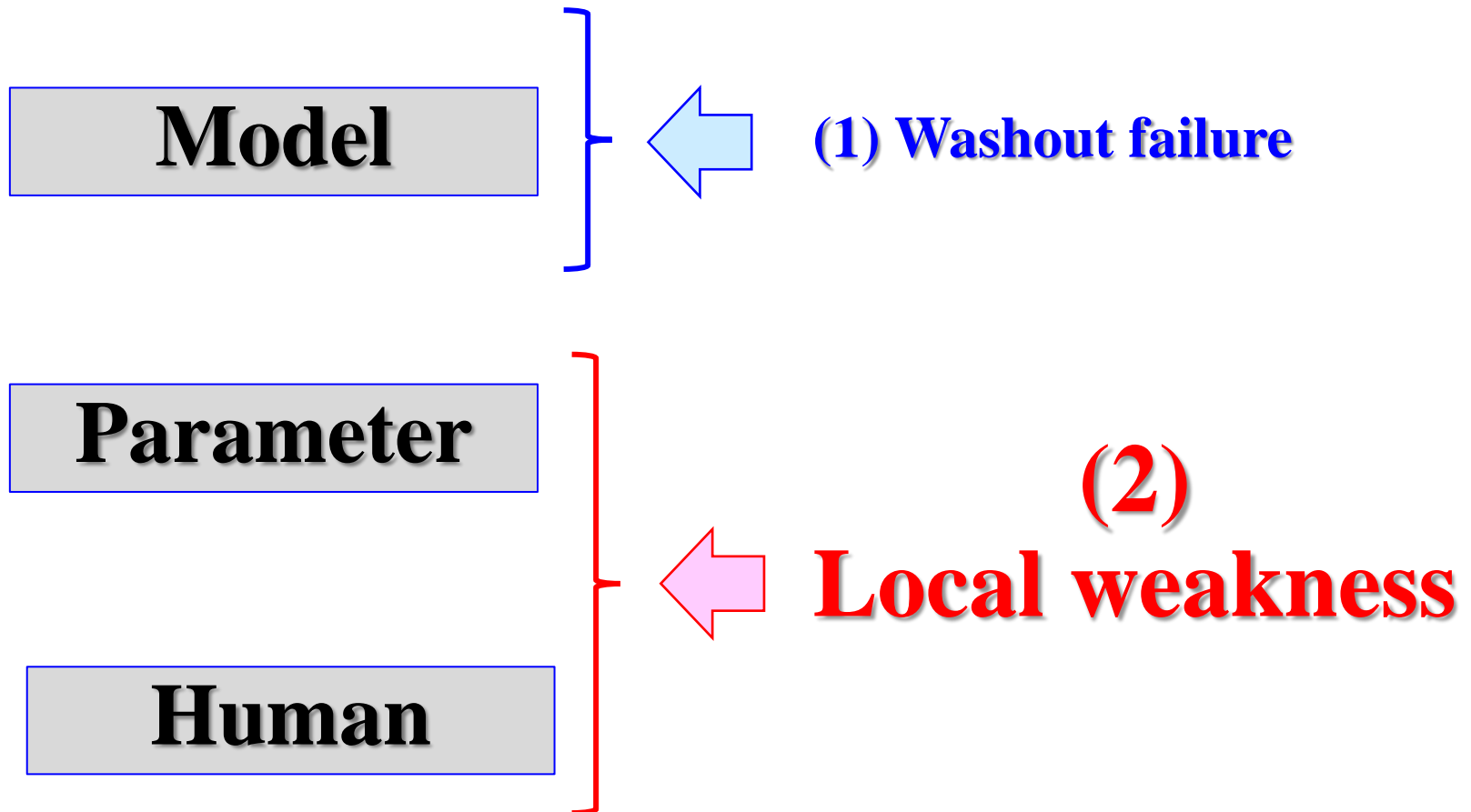
Triggered by burst of water main, mobile but

NOT washout failure

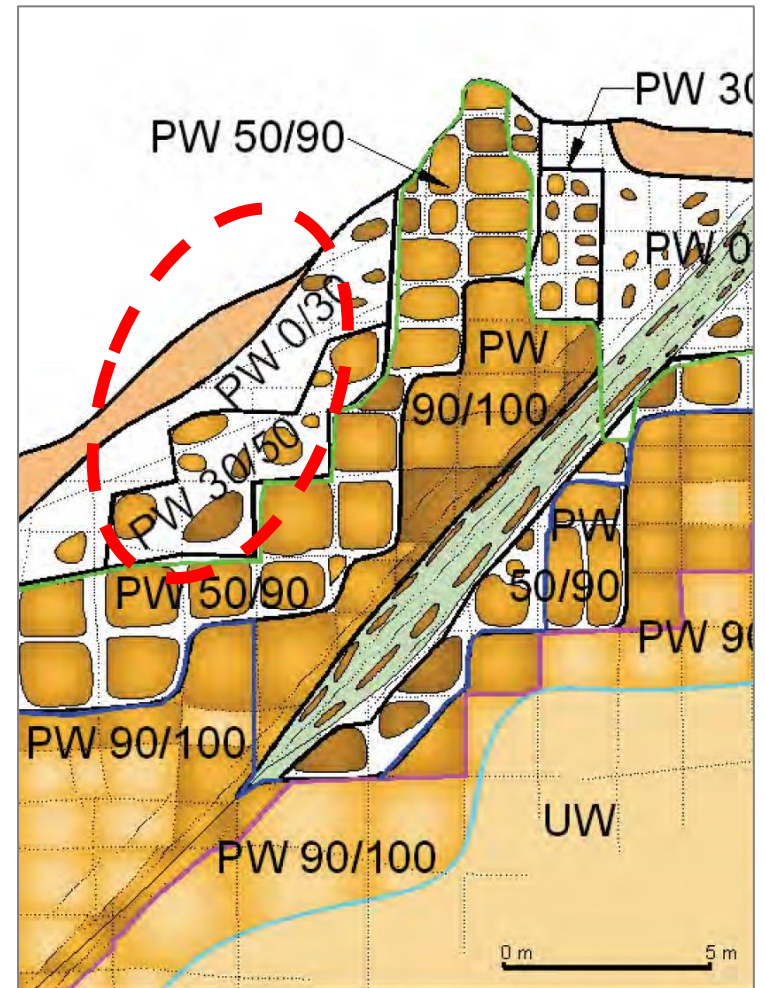
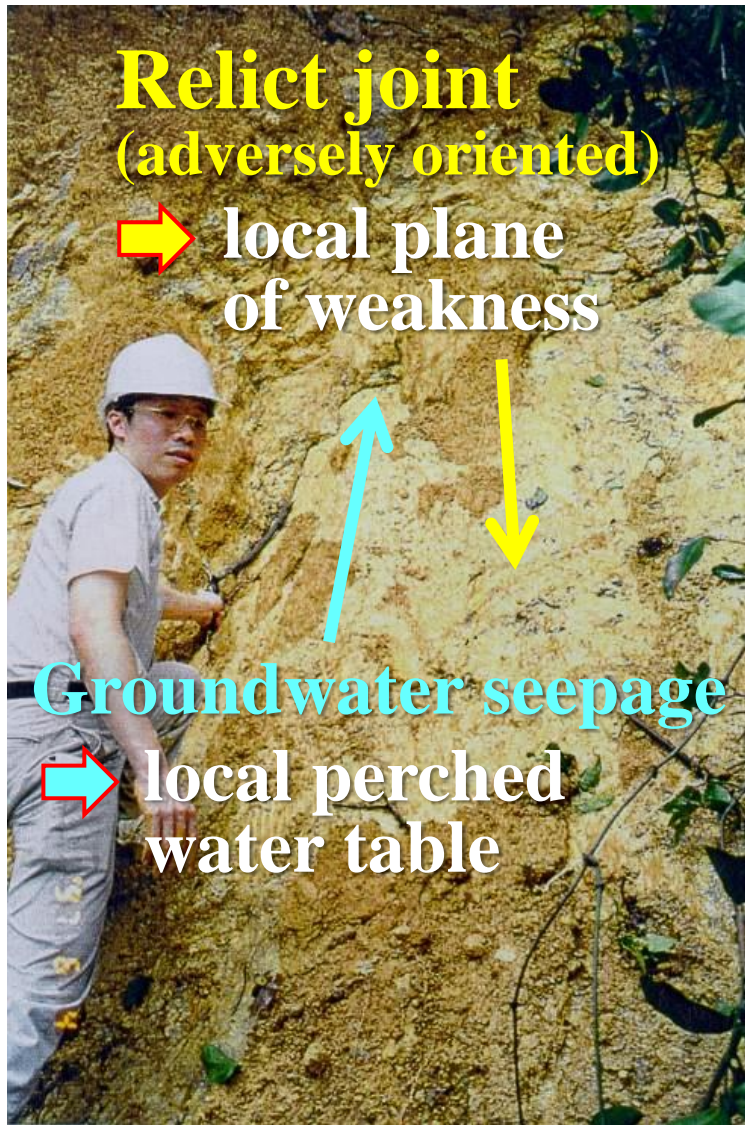


Schematic Cross-section

Morgenstern (1995 & 2000)

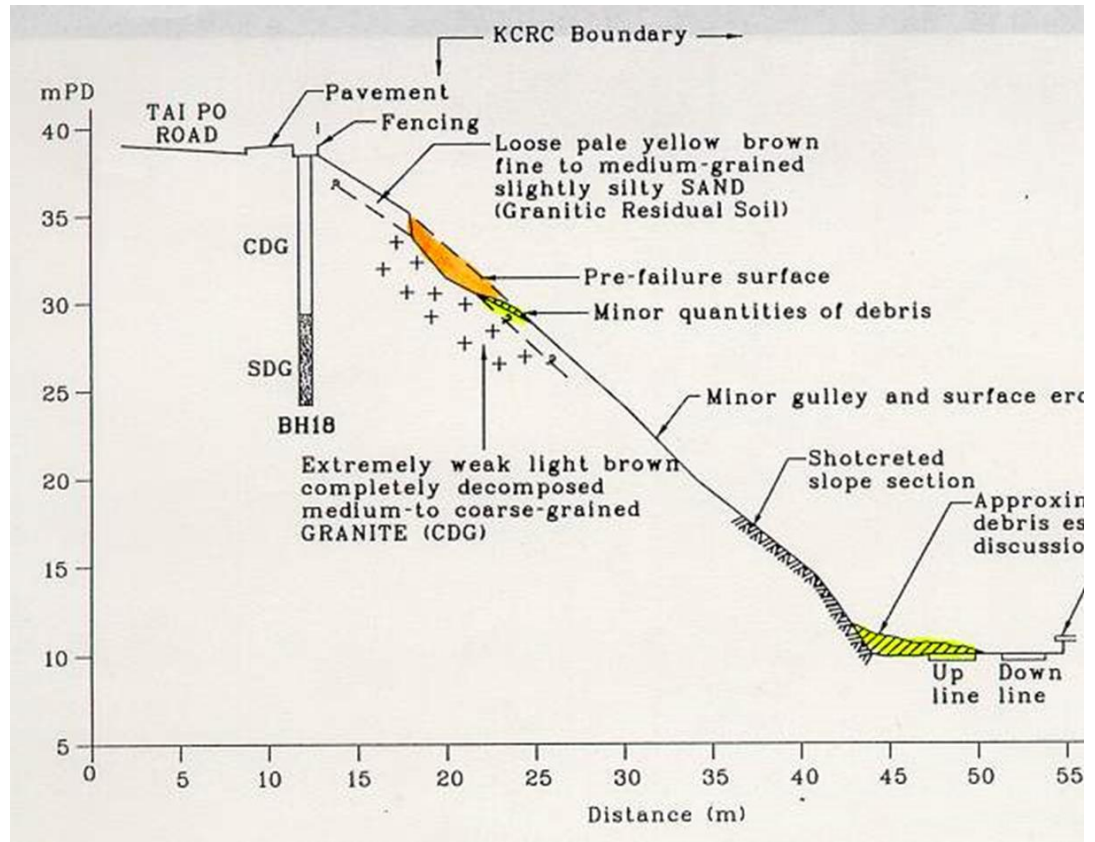


Local weakness: Relict Discontinuities



Weathered profile in saprolite
(from *Geoguide 3*)

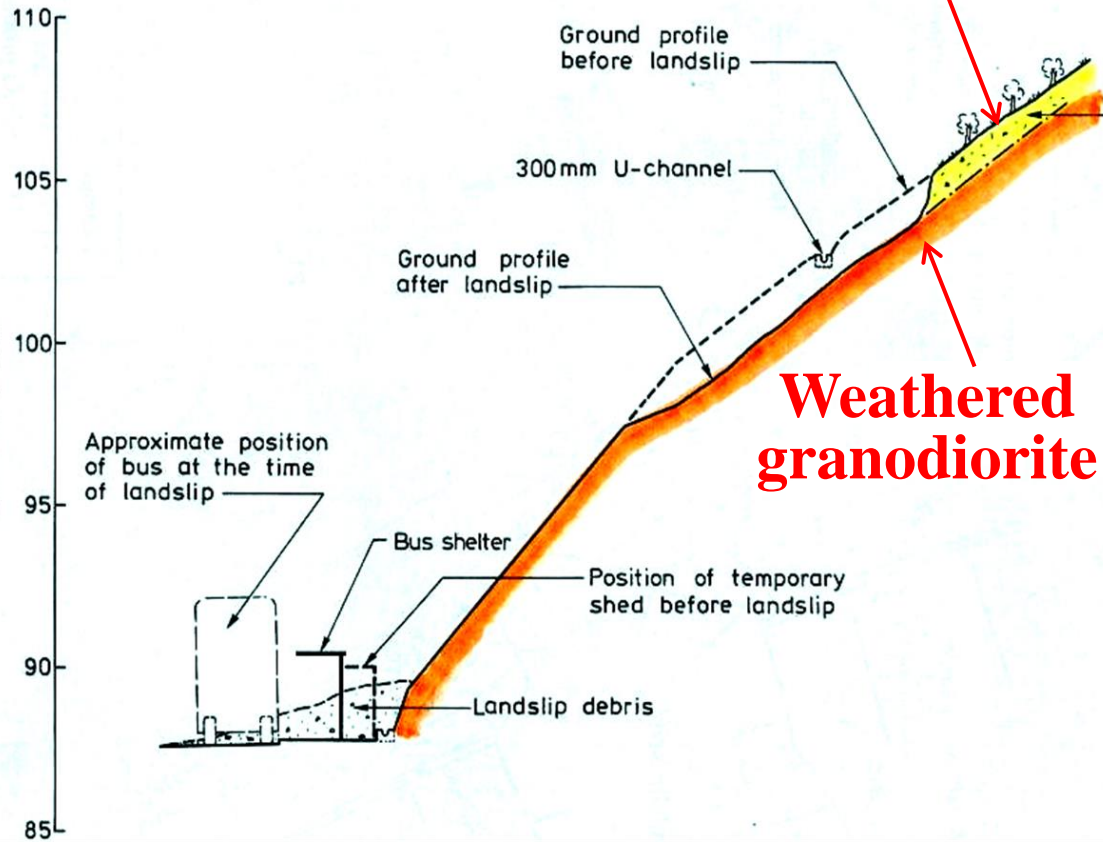
1997 University Station (20 m³)



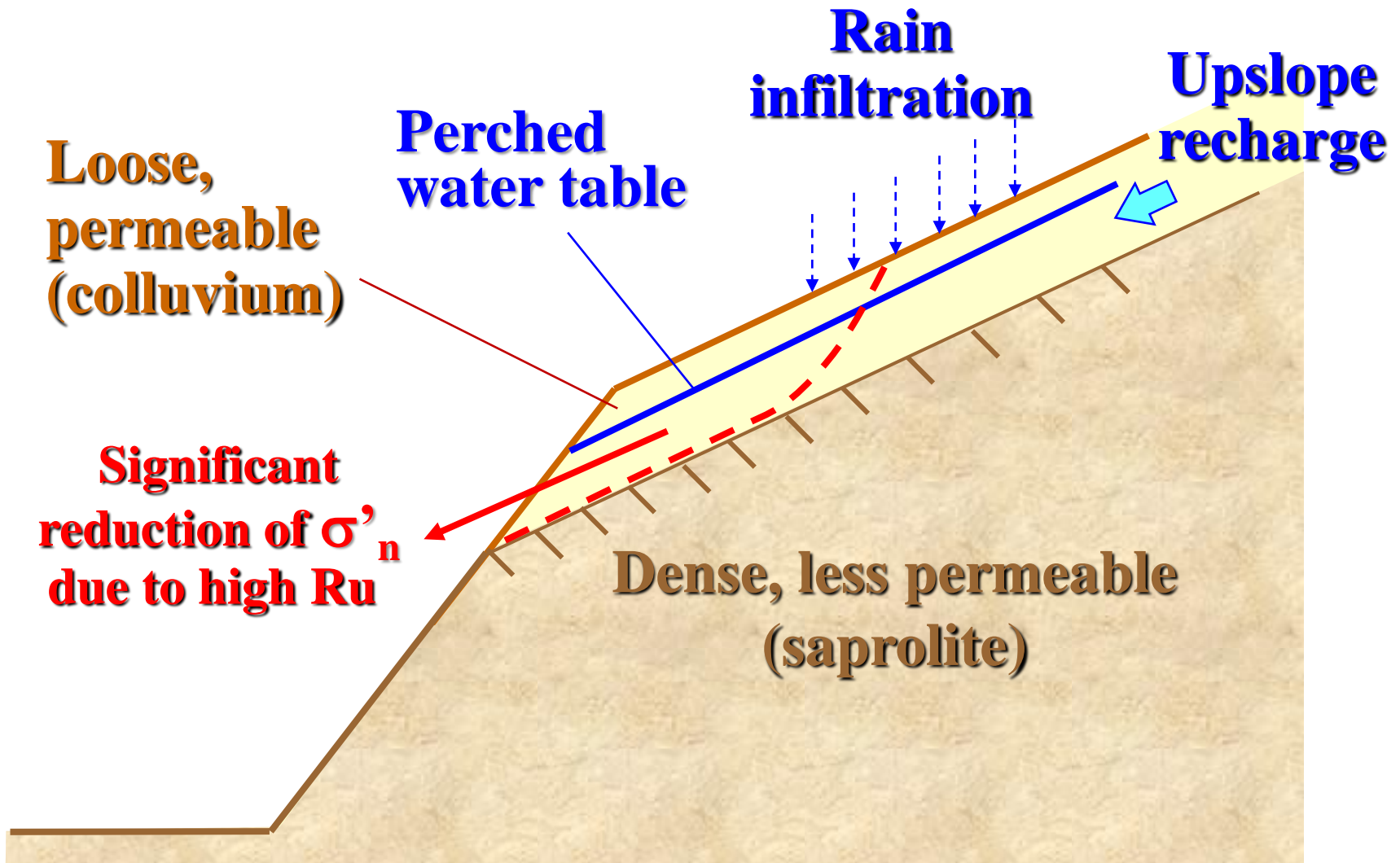
1993 Cheung Shan Estate (50 m³, 1 fatality)

Colluvium

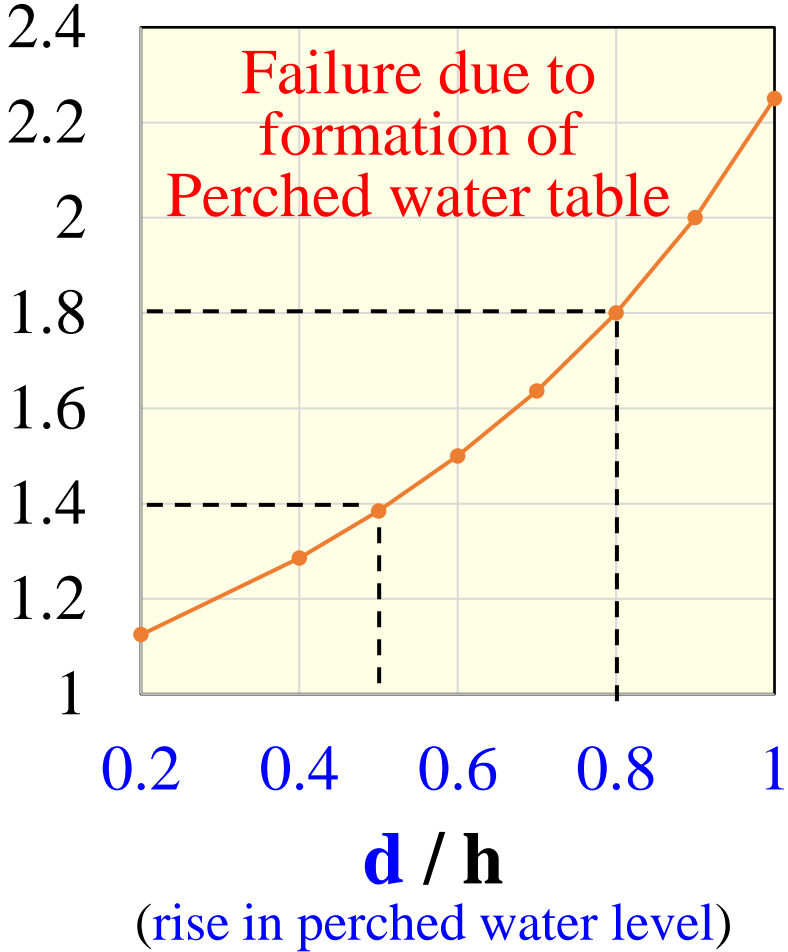
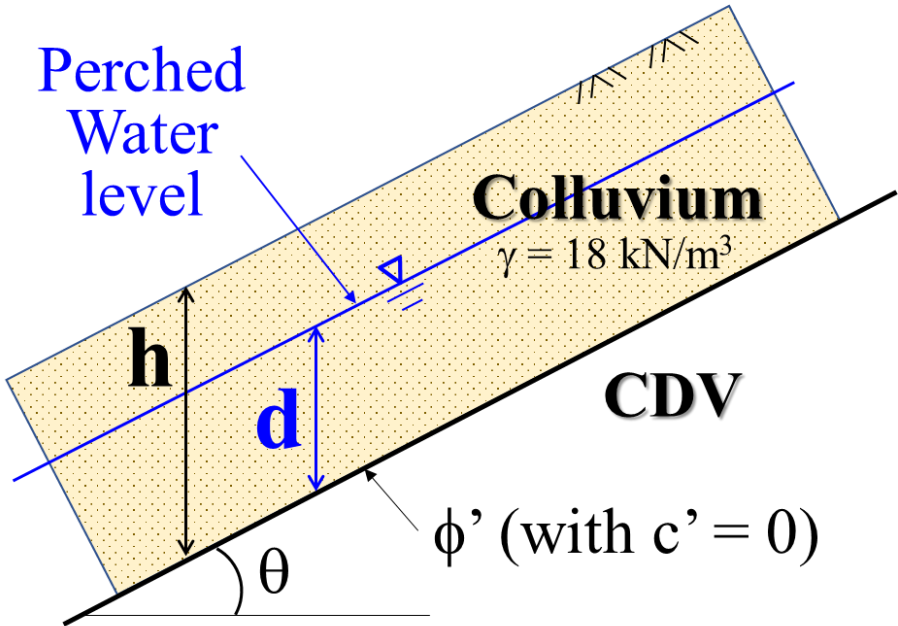
Weathered granodiorite

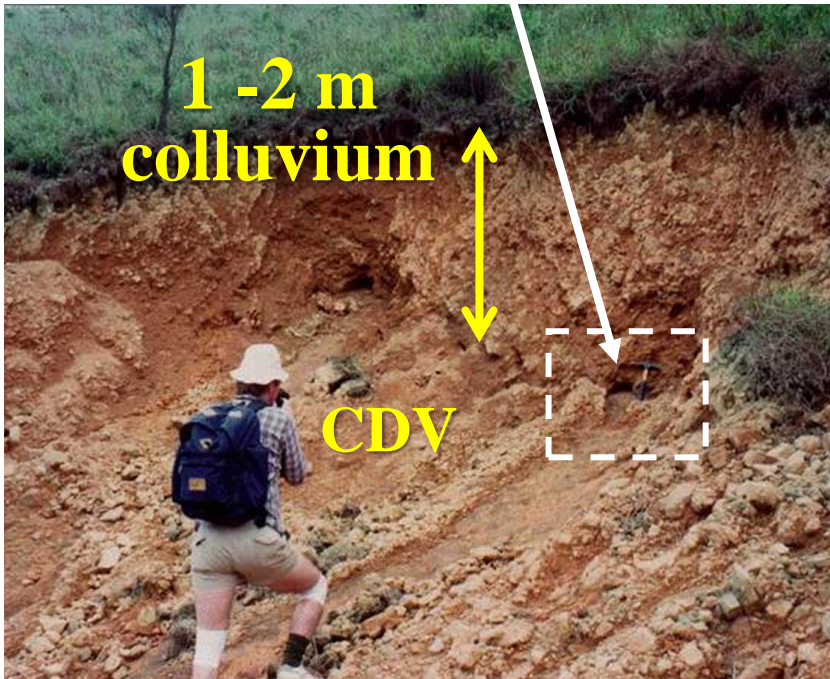
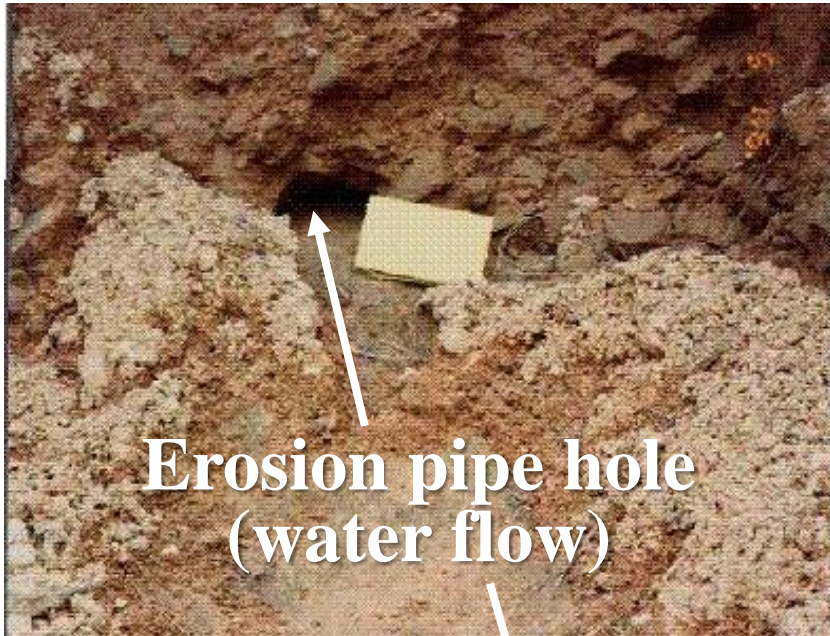


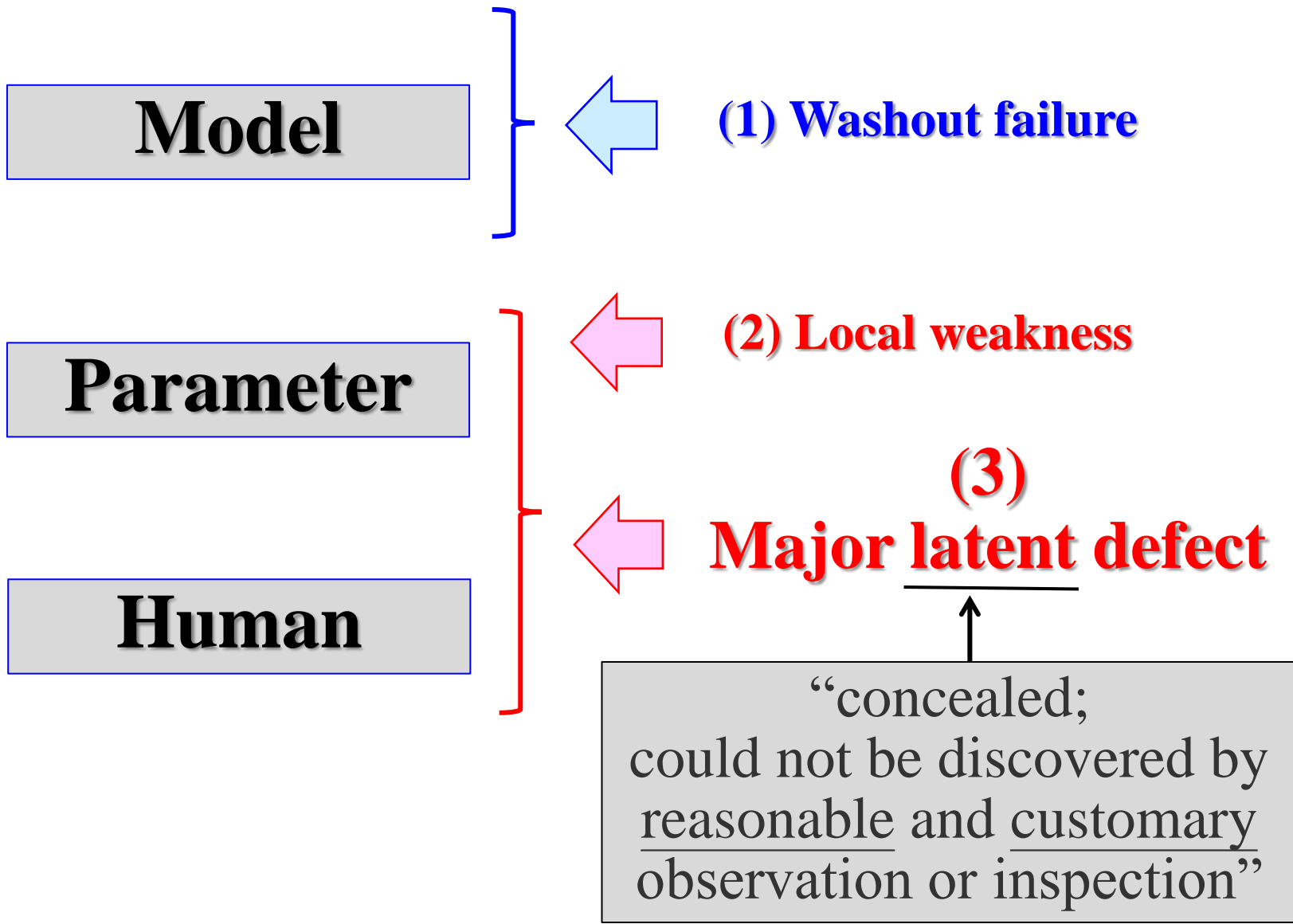
Perched Water Table (near slope crest)



Original FOS (if $d = 0$)







1997 Hong Tsuen Road (250 m³)

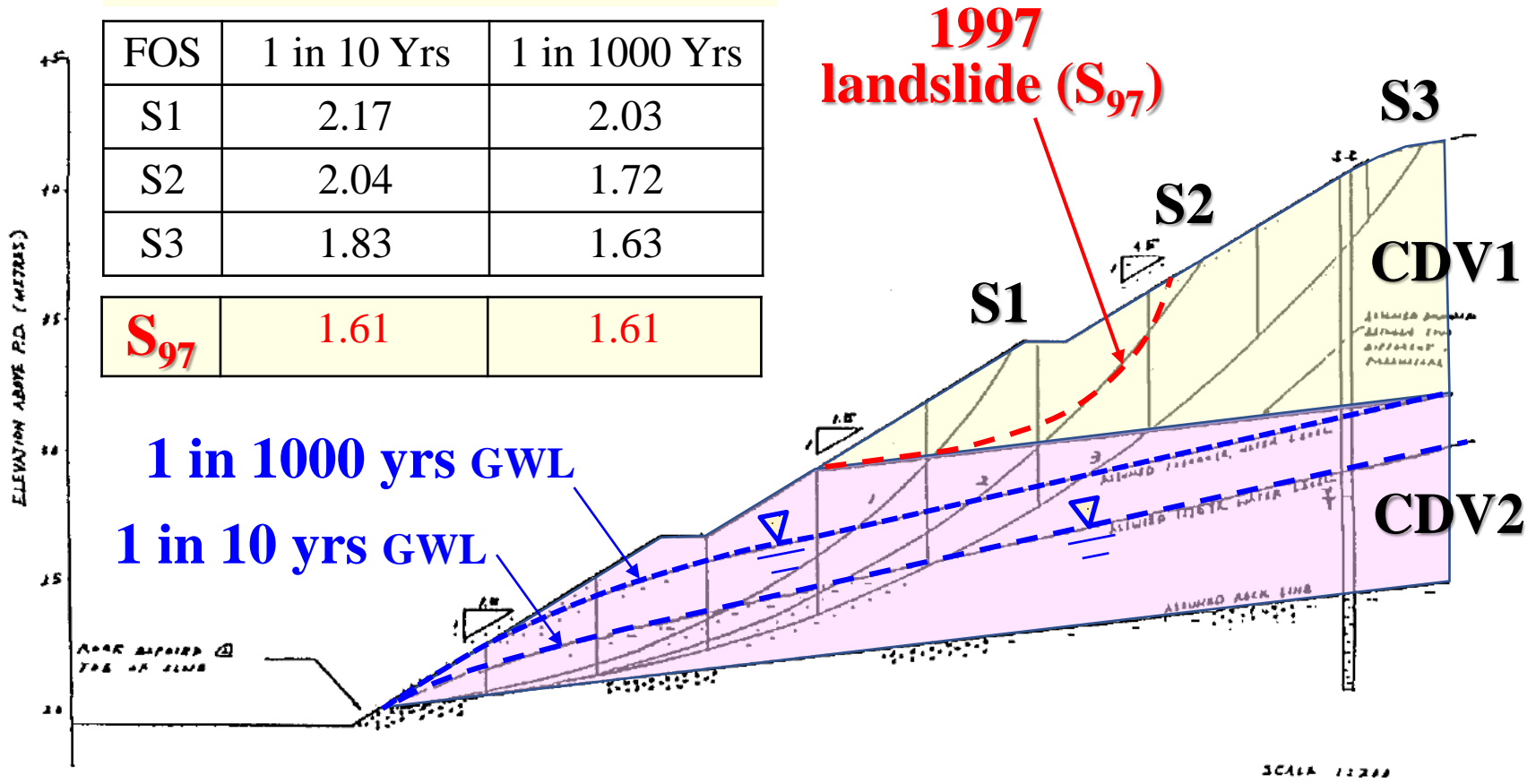


Government slope
formed in 1981
(16 yrs before 1997 landslide)

Design Cross-section

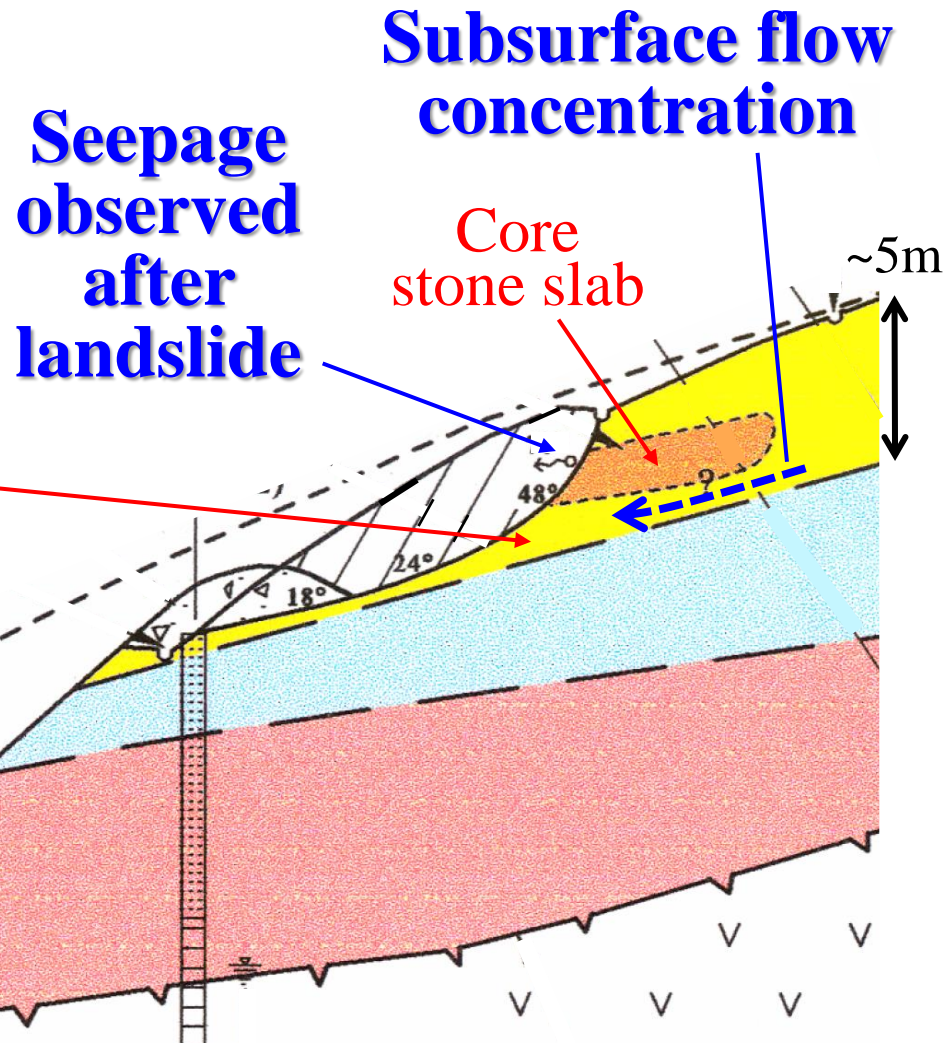
Design parameters for CDV1:
 $c' = 0$; $\phi' = 37^\circ$; $\gamma = 18 \text{ kN/m}^3$

FOS	1 in 10 Yrs	1 in 1000 Yrs
S1	2.17	2.03
S2	2.04	1.72
S3	1.83	1.63
S₉₇	1.61	1.61

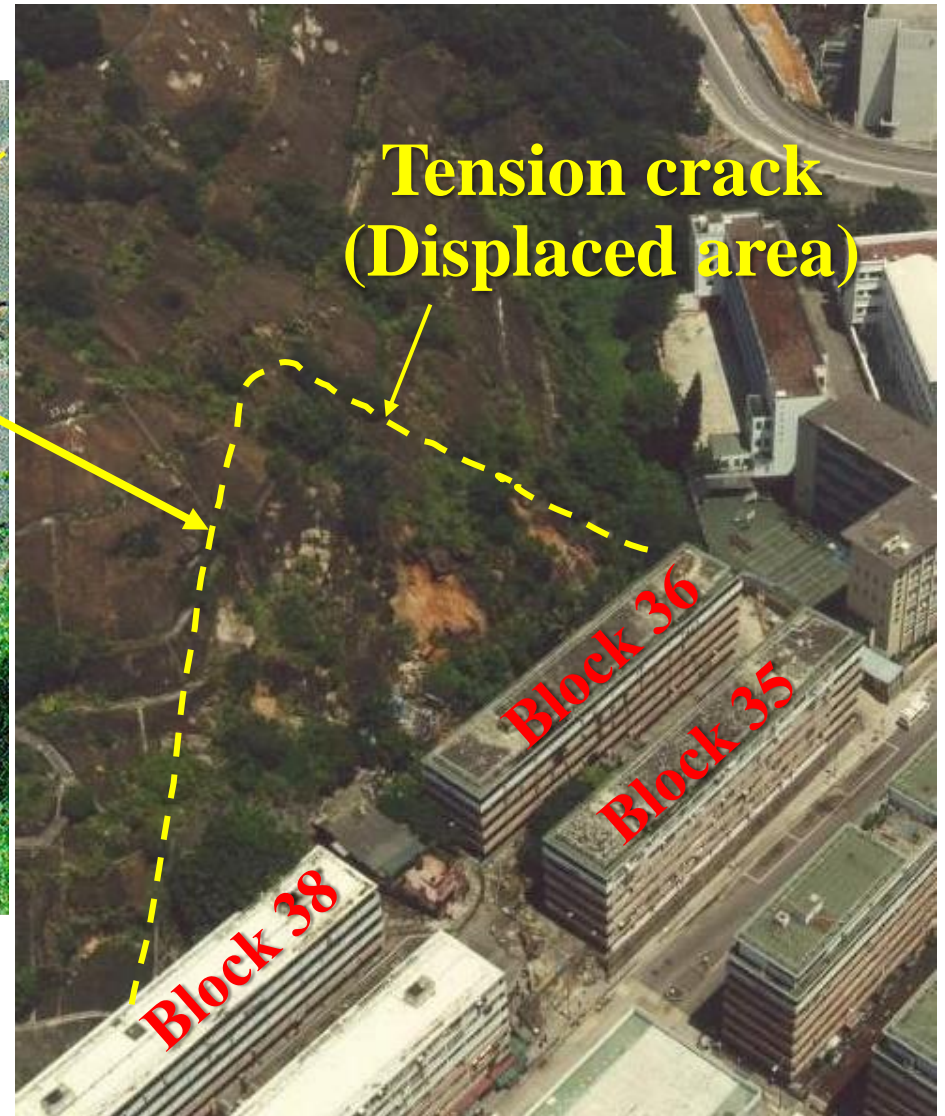
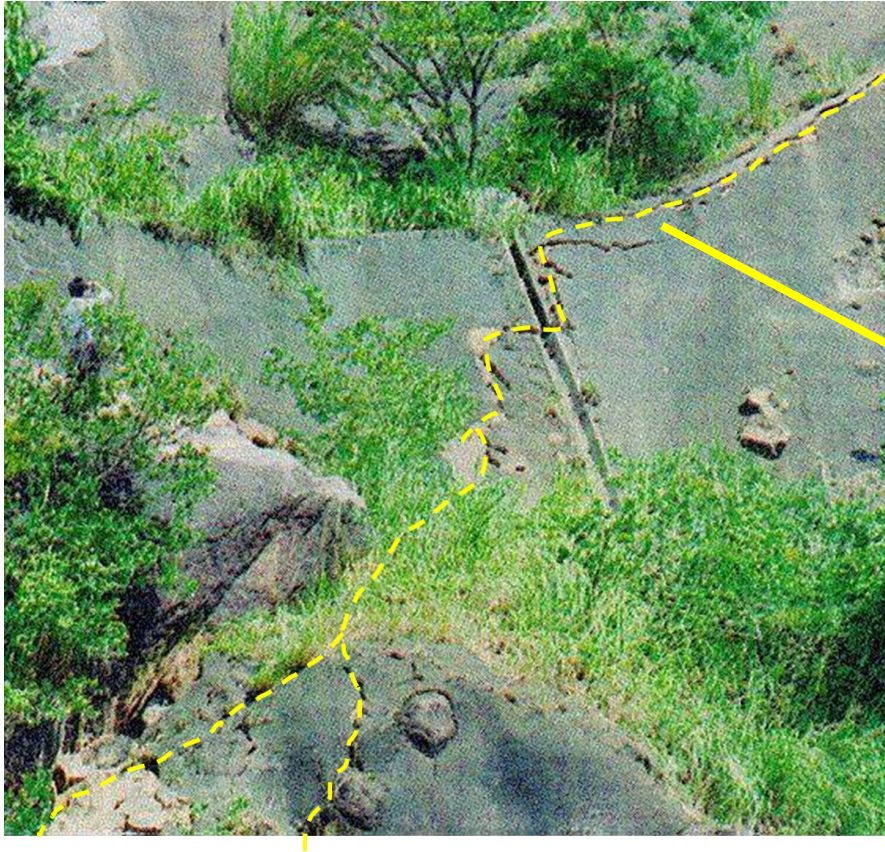


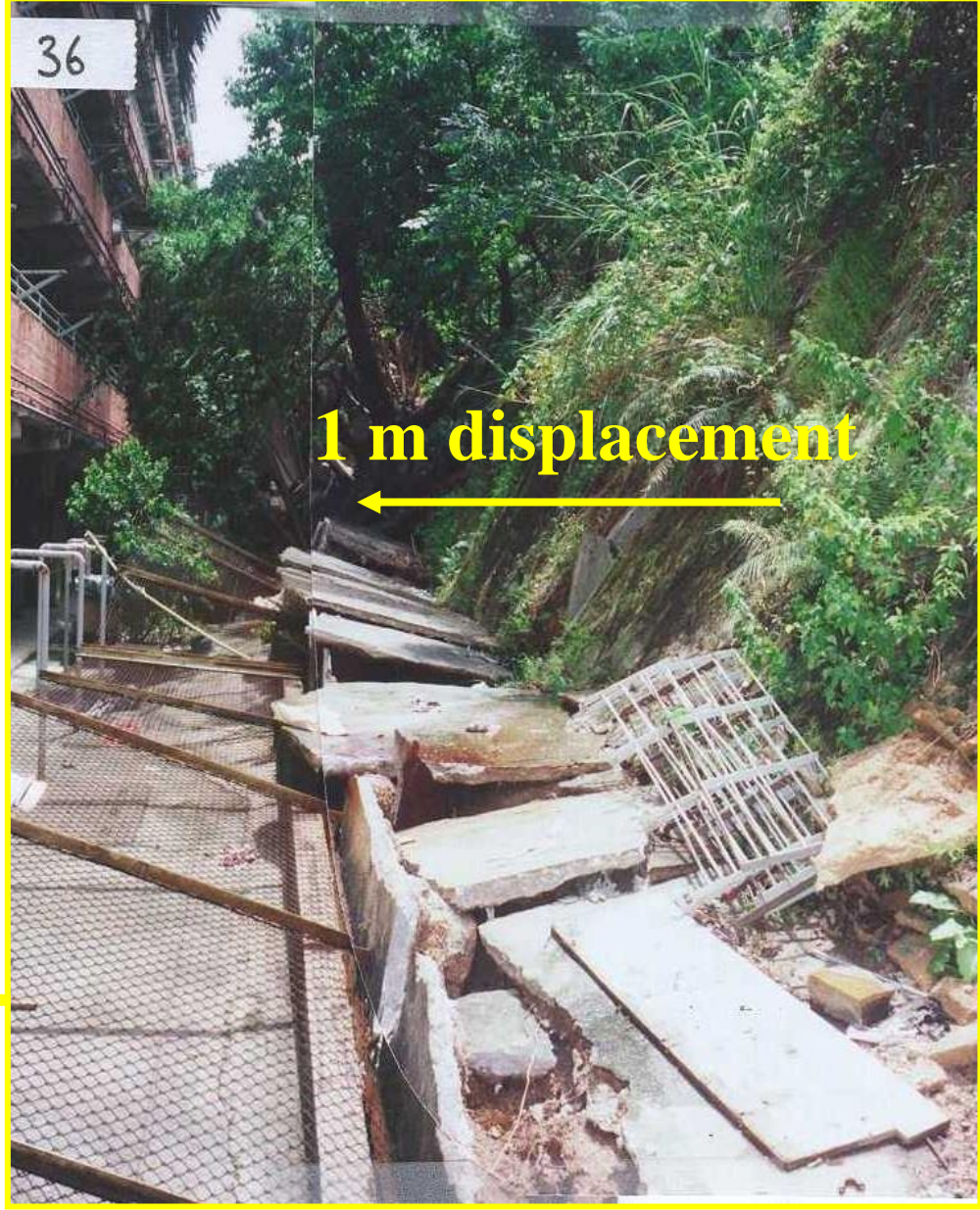
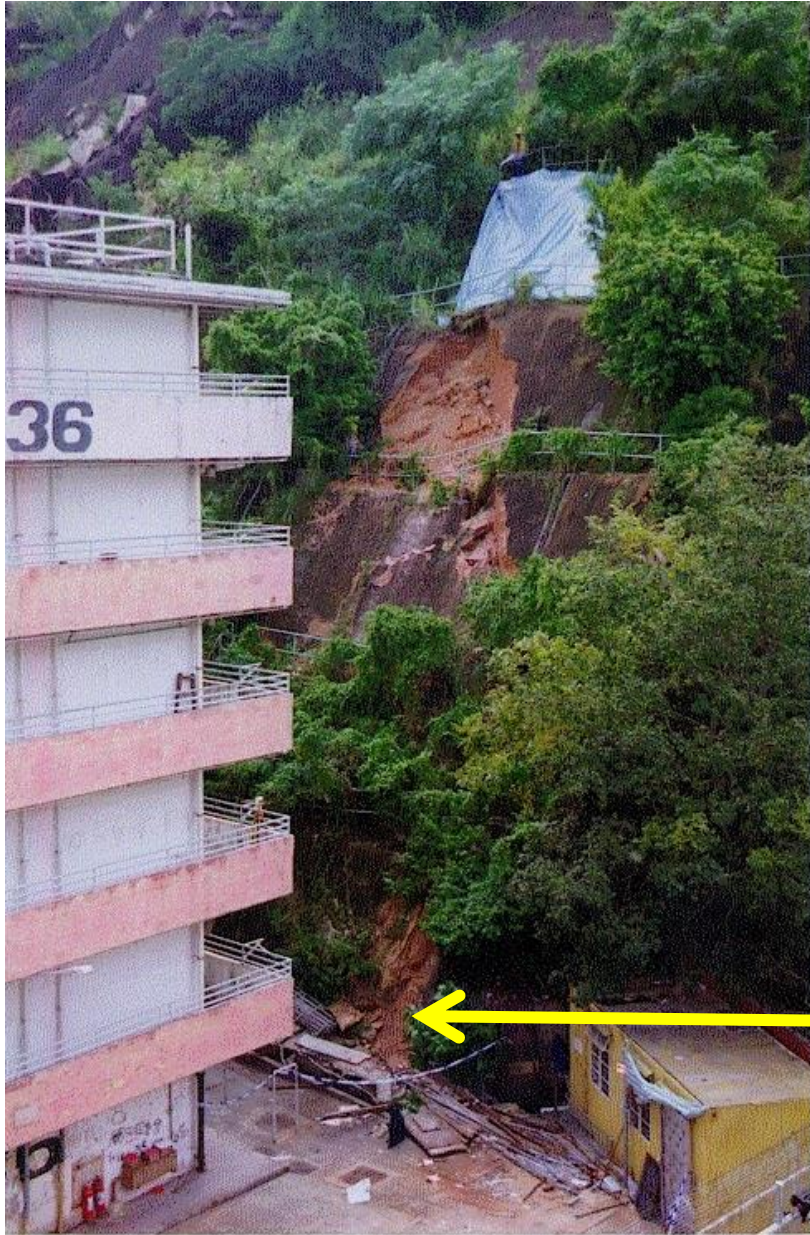
Clay-rich CDV

(with low permeability bands)

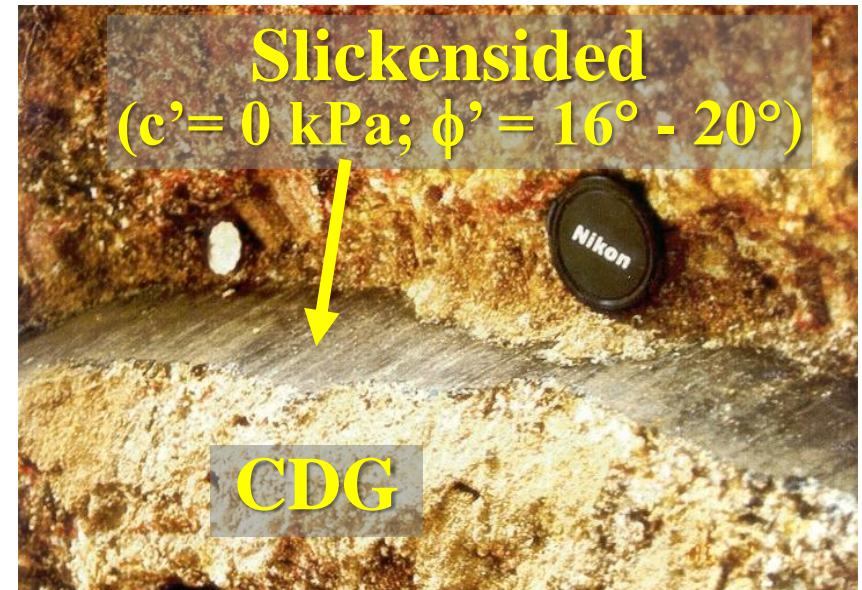
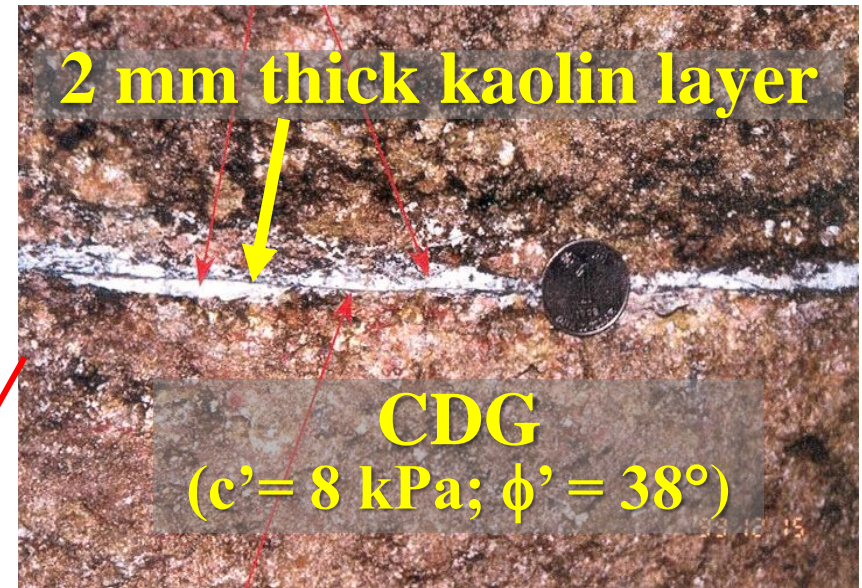
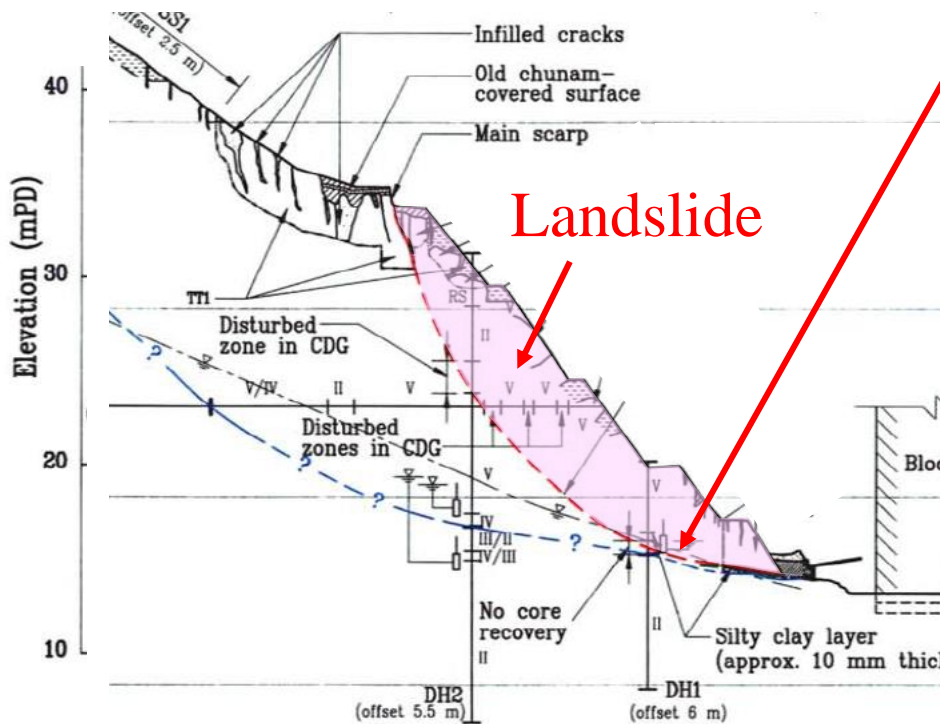


1999 Shek Kip Mei (6000 m³)



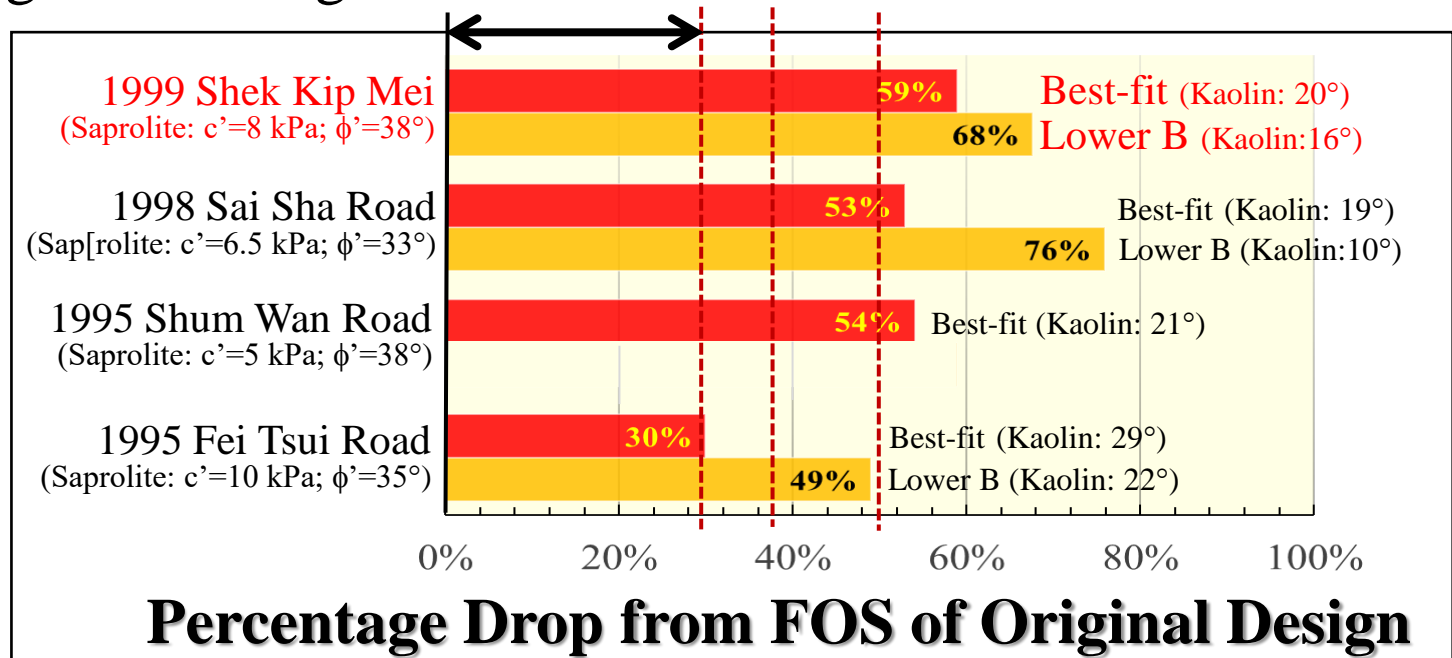


Failure controlled by Kaolin-rich discontinuities

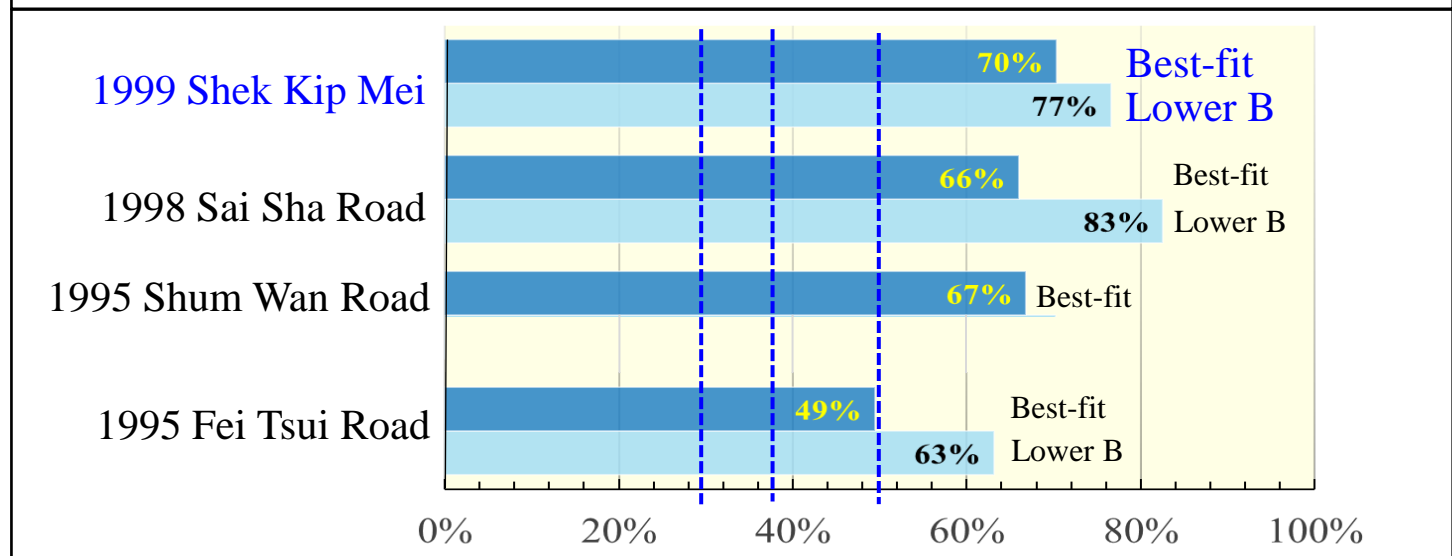


Safety margin from original FOS = 1.4 1.6 2.0

**Due to
kaolin-rich
structures**



**Due to
kaolin-rich
structures
and
elevated
water level**

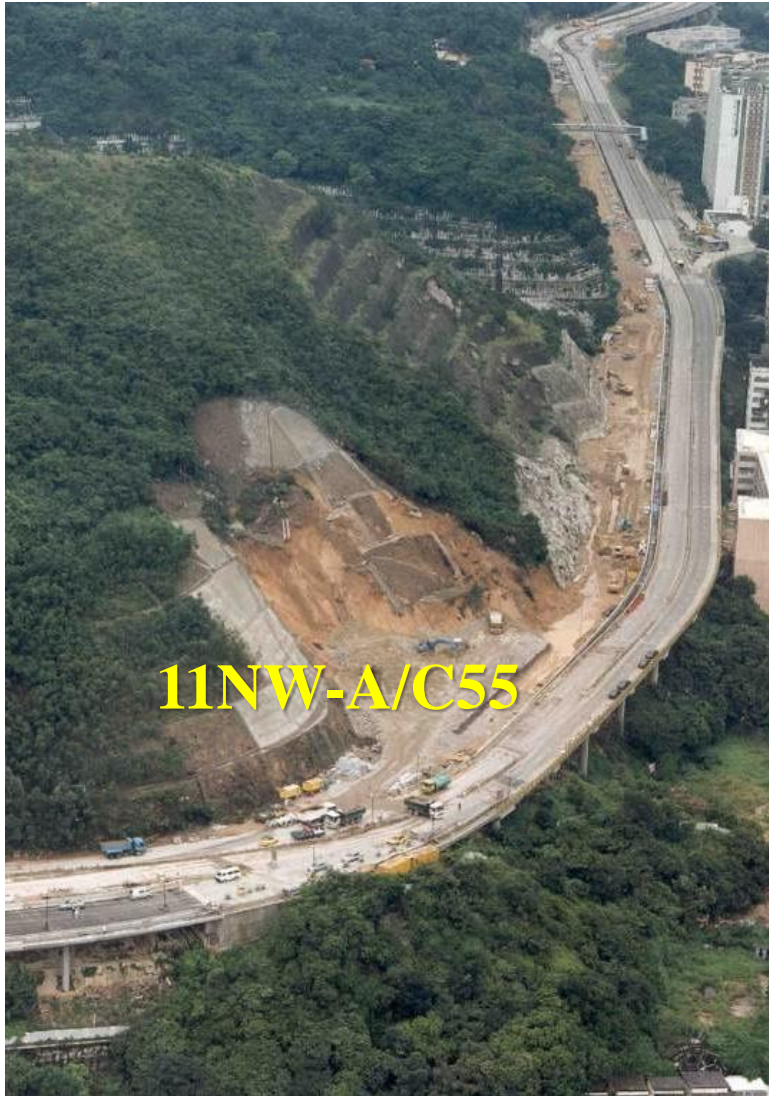


Lamb vs Lion

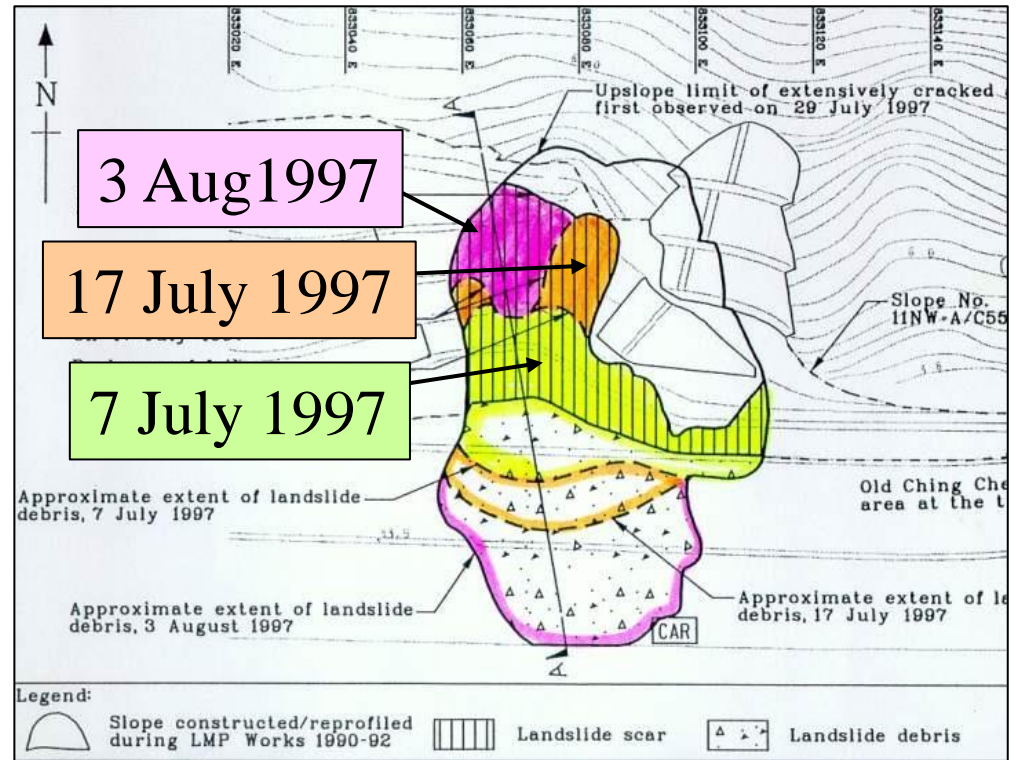
Roman Soldier



1997 Ching Cheung Road (5000 m³)

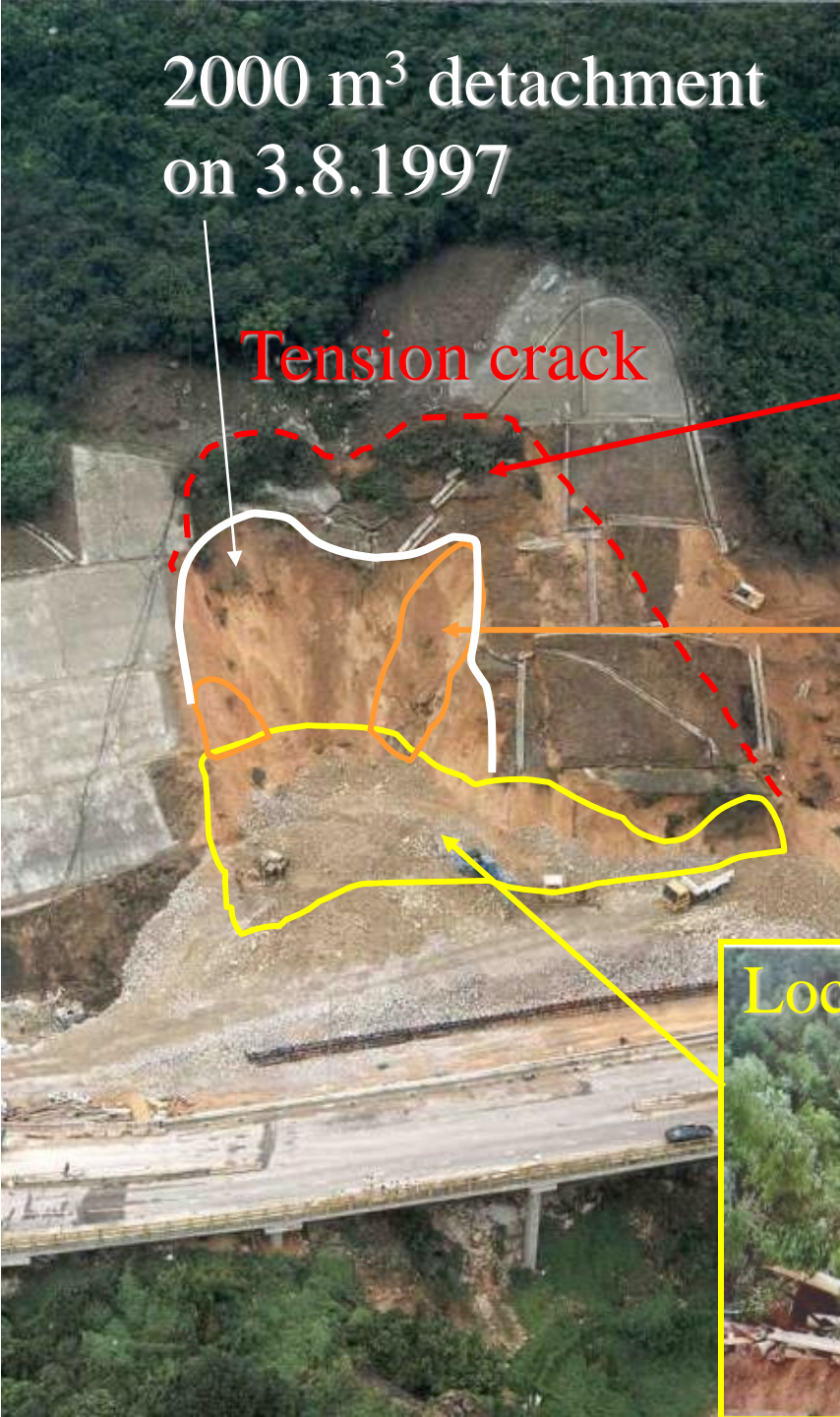


Three 'Phases' of Detachment



2000 m³ detachment
on 3.8.1997

Tension crack



Tension crack (29.7.1997)



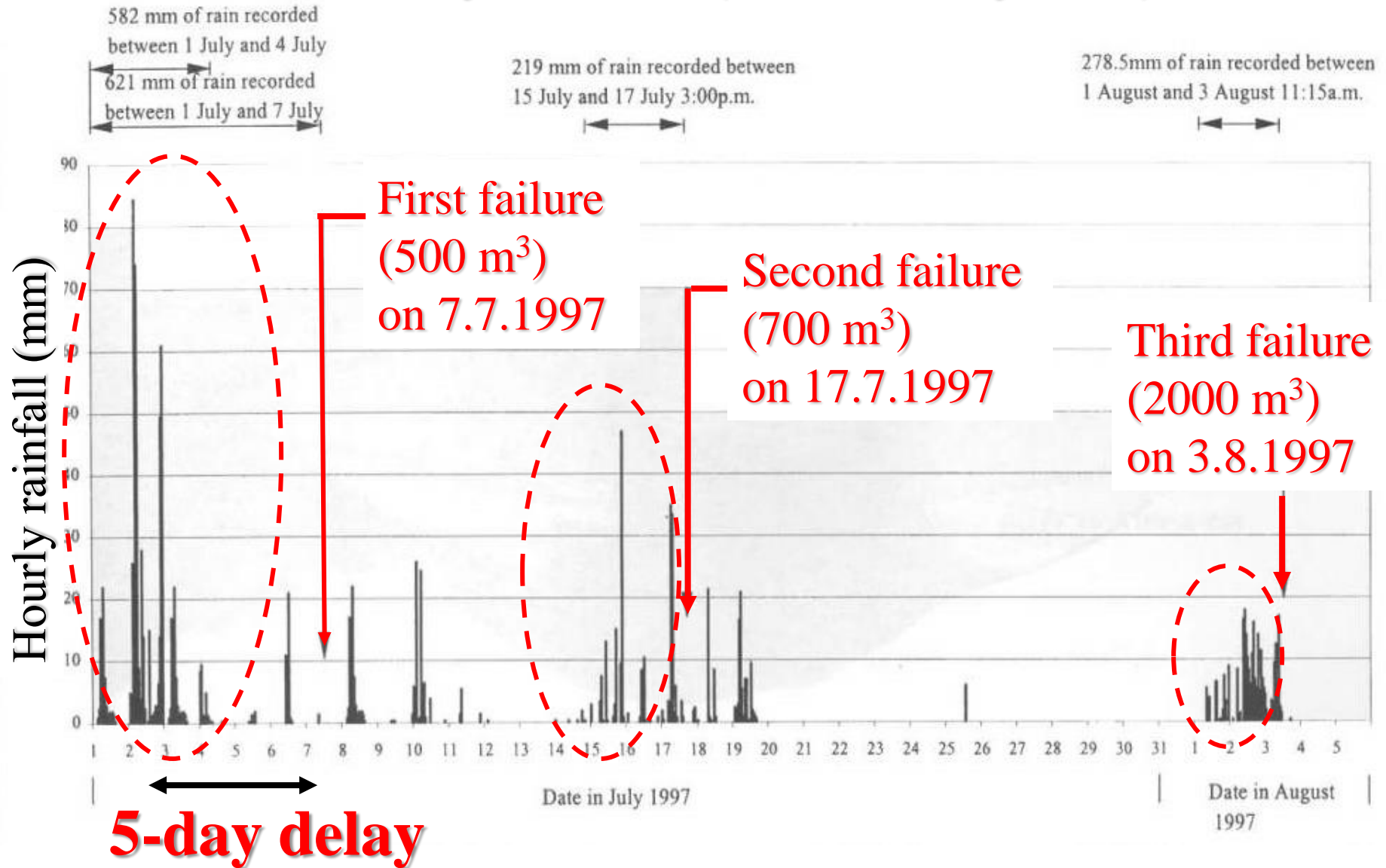
Further detachment 700 m³ (17.7.1997)



Local detachment 500 m³ (7.7.1997)

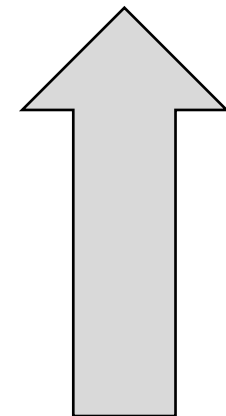
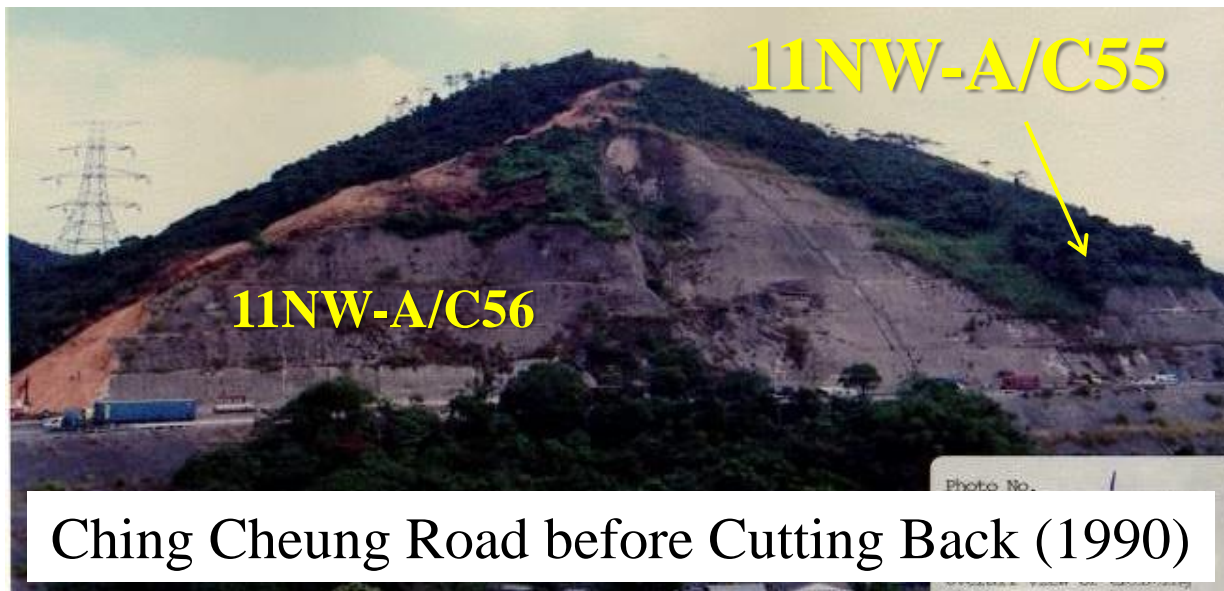


Delay Failure (w.r.t. heavy rain)





Landslip
preventive
works
(cutting back)
by GEO
in 1991-92



Bridging the Gap between Theoretical and Actual Slope Performance

(3) What have we done ?

Enhanced Slope Engineering & Management

Prescriptive measures
(+ attend to surface water)

(1) Washout failure

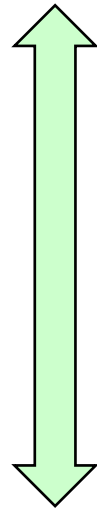
(Mixed, usually smaller scale)

(2) Local weakness

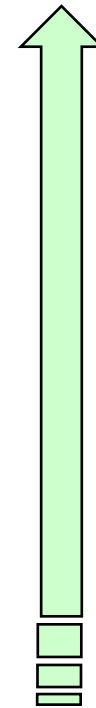
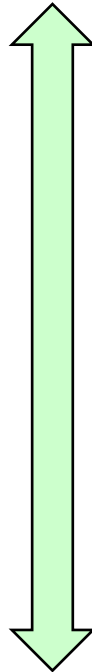
(Smaller scale)

(3) Major latent defect

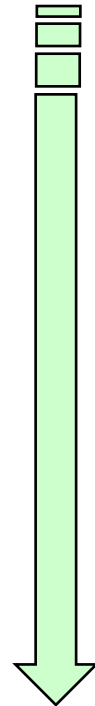
(Larger scale)



Robust design



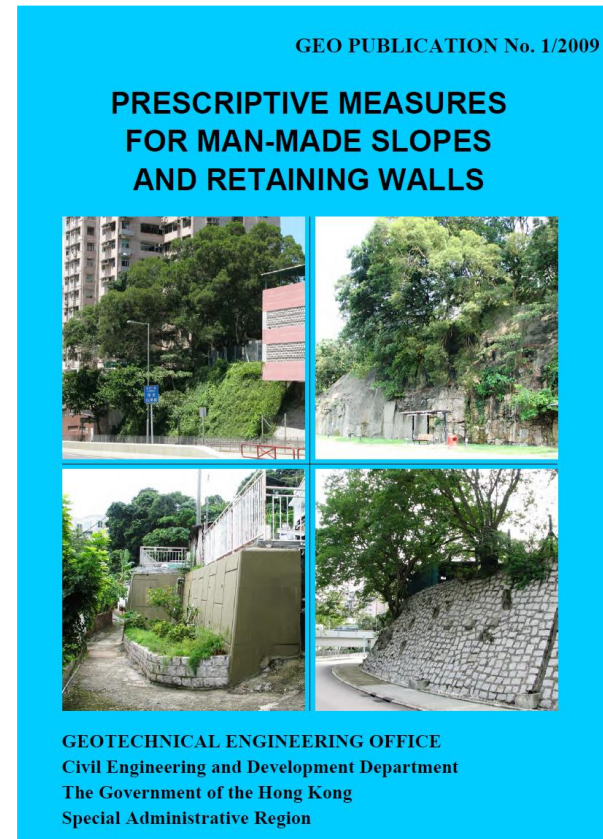
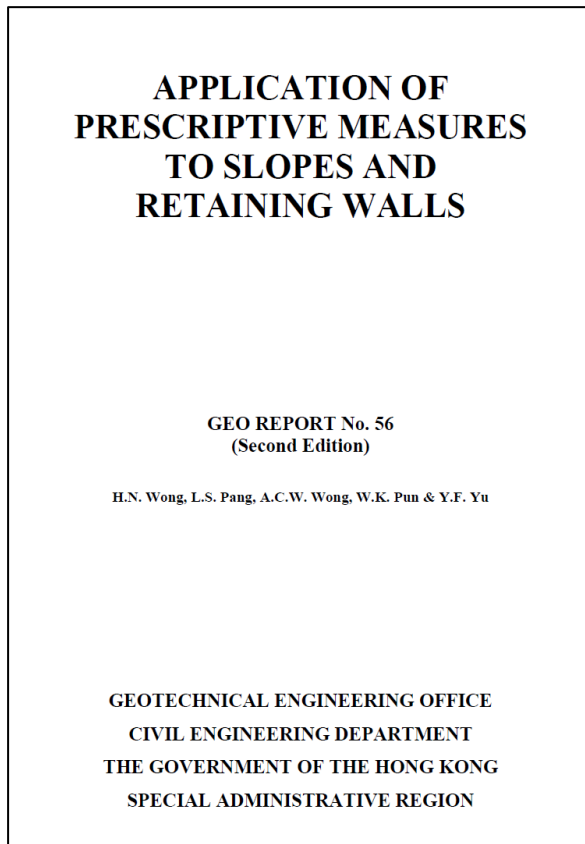
Emergency response



Slope maintenance

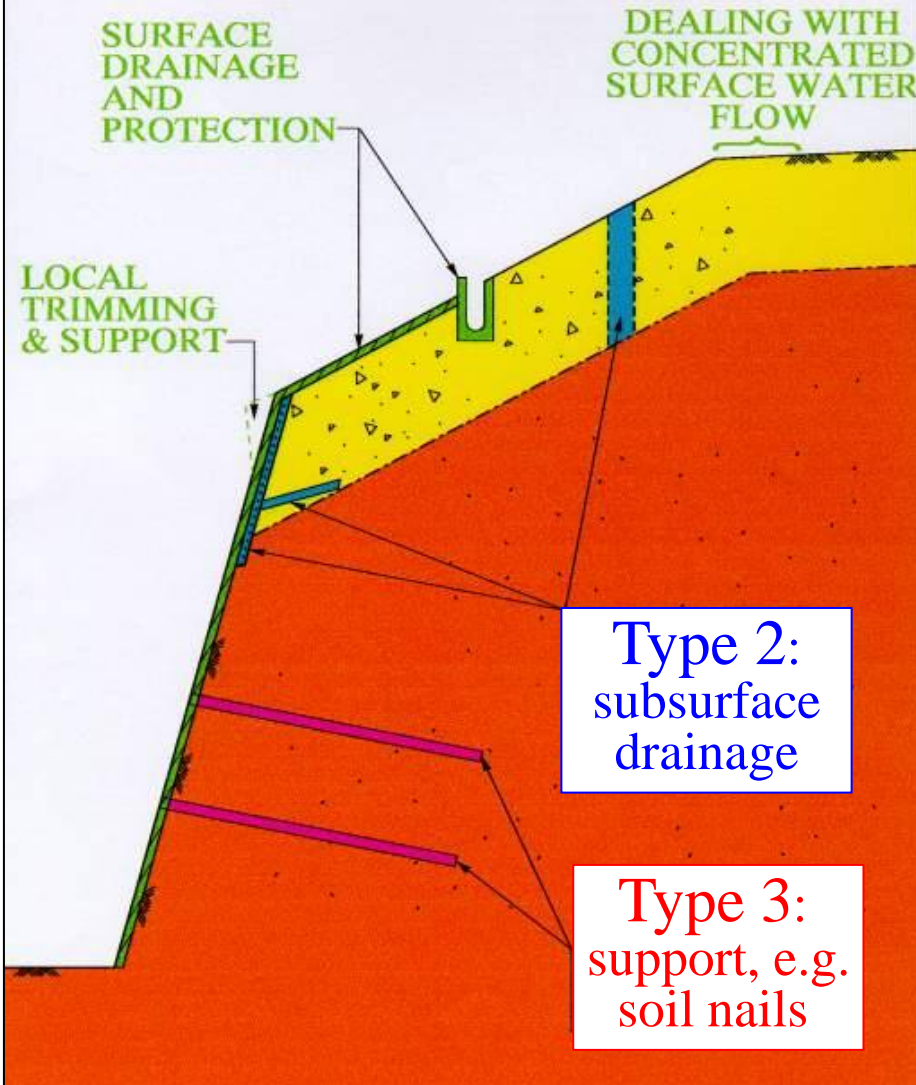
Prescriptive Measures

pre-determined, experienced-based and suitably conservative modules of works prescribed to improve stability or reduce risk, without detailed ground investigation and design analysis



Prescriptive Measures

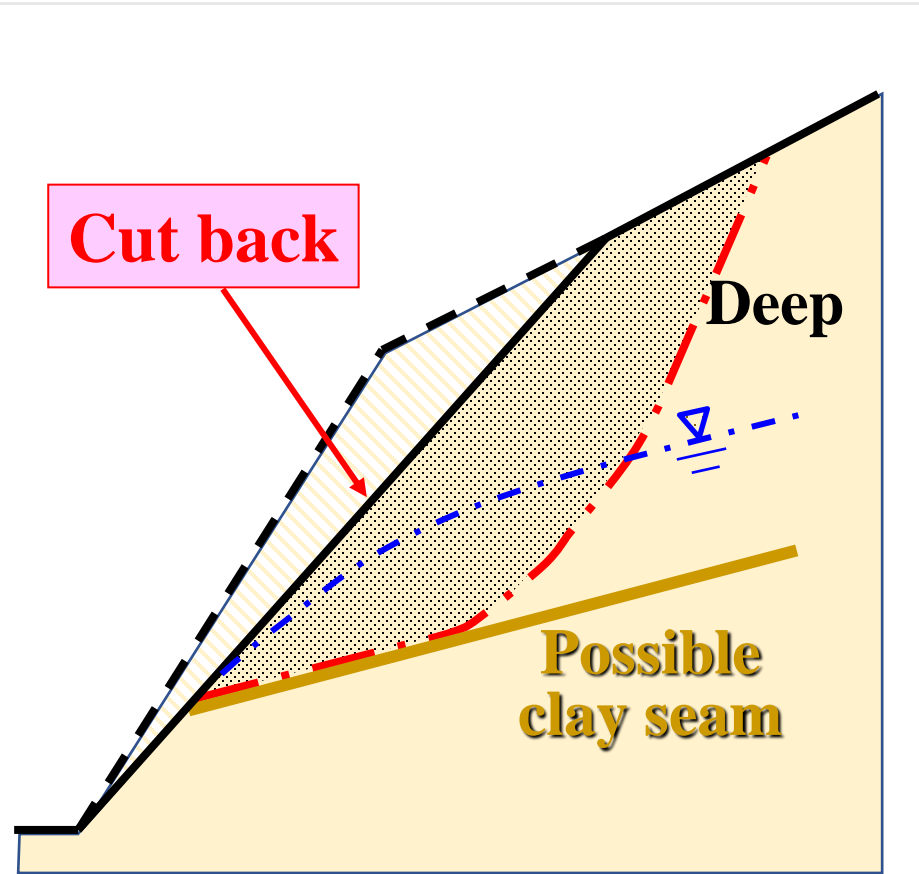
Type 1: surface drainage & protection



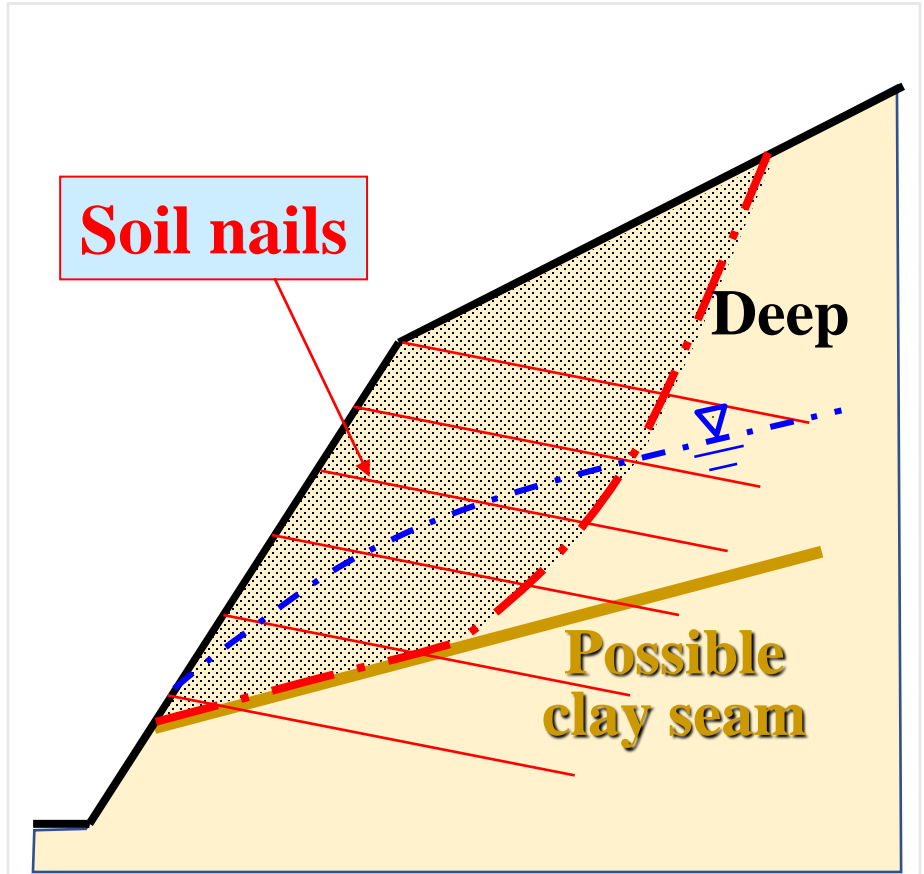
Improved drainage detailing



Robust Design Scheme (e.g. soil nailing)

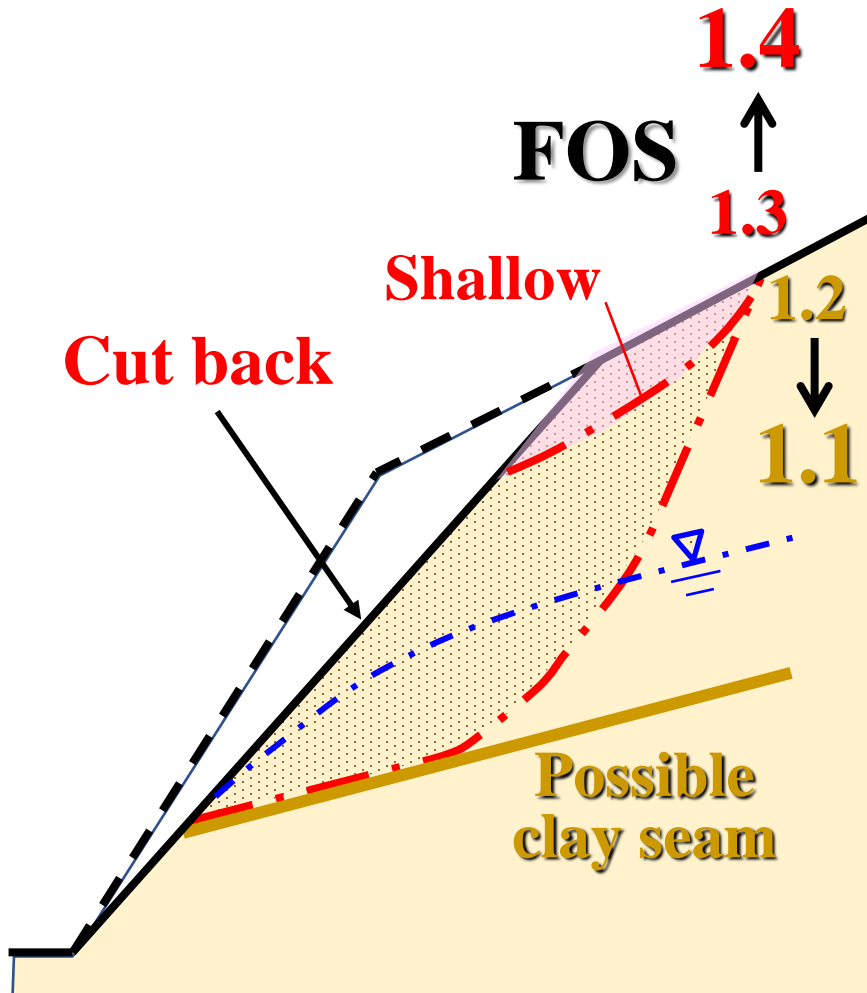


Very sensitive to uncertainties



Less sensitive to uncertainties

Effect of Cutting Back on FOS



**Design intent:
cut back to increase FOS**

**But:
may reduce FOS
of failure
controlled by
latent defect or
local weakness**

Robust scheme: soil nailing

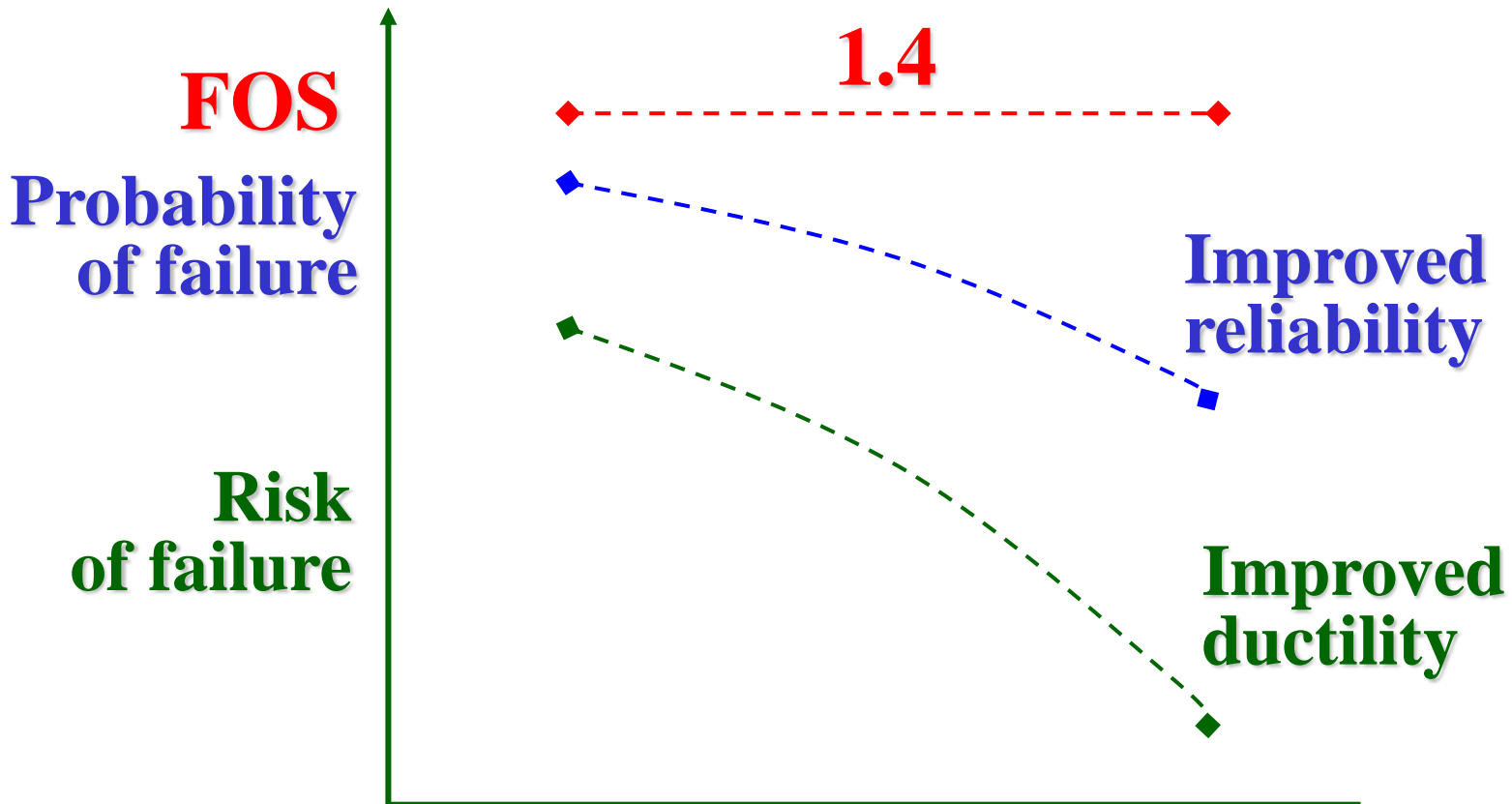
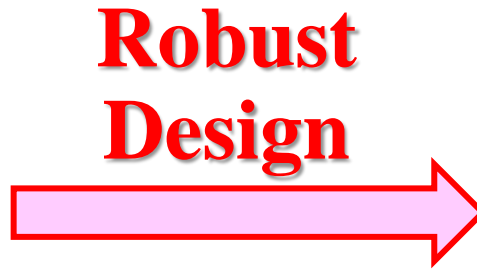
Improved reliability:

- Less sensitive to adverse ground conditions
- Less vulnerable to local failure (large integral mass)

Improved ductility:

- Slope deformed for days/weeks before full detachment





Slope Maintenance (since late 1990s)

... to avoid deterioration and upkeep function

Geoguide 5

Guide to Slope Maintenance

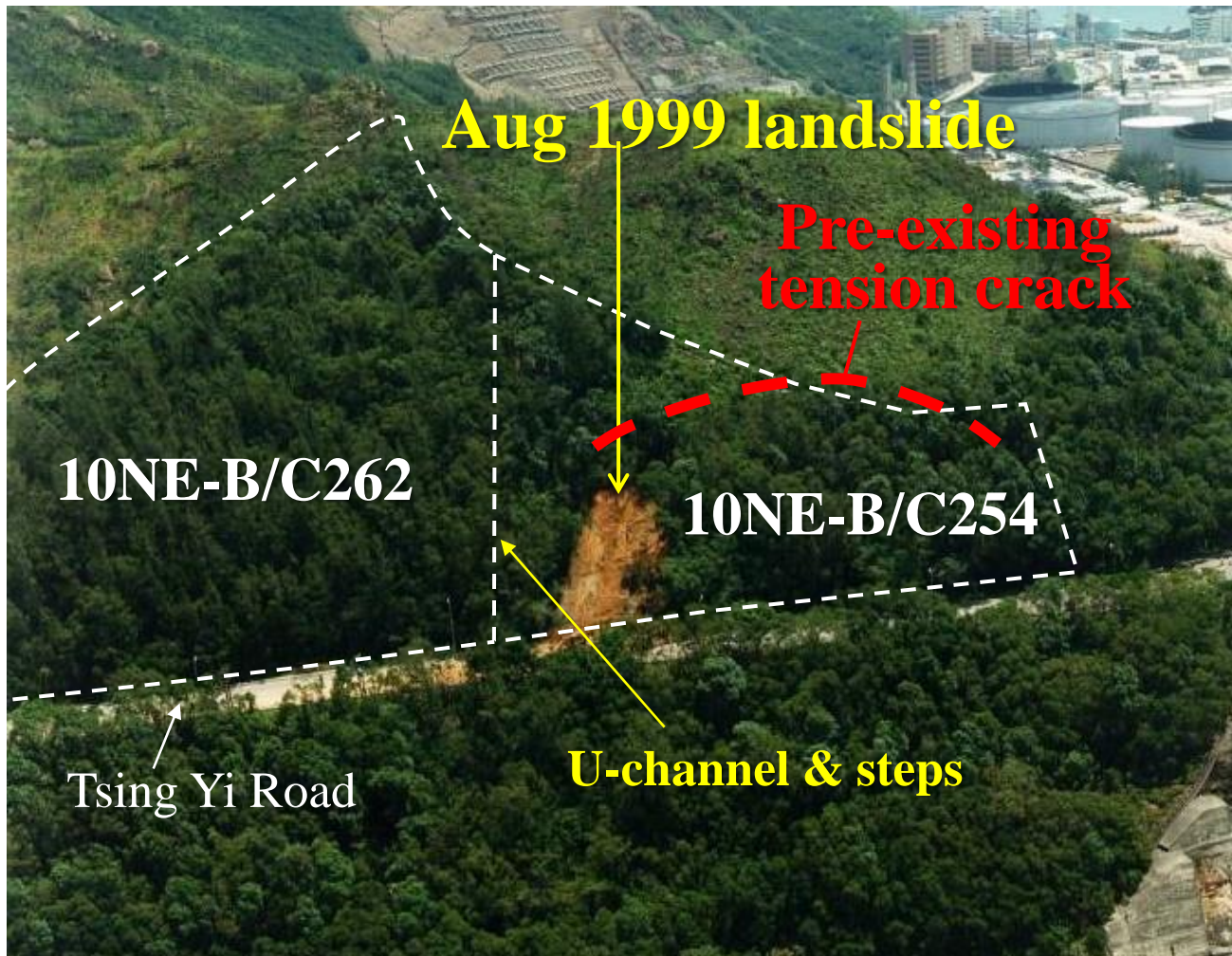
Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

- Routine inspections and maintenance
- Engineer Inspections
- Checks of buried water-carrying services
- Monitoring of special measures



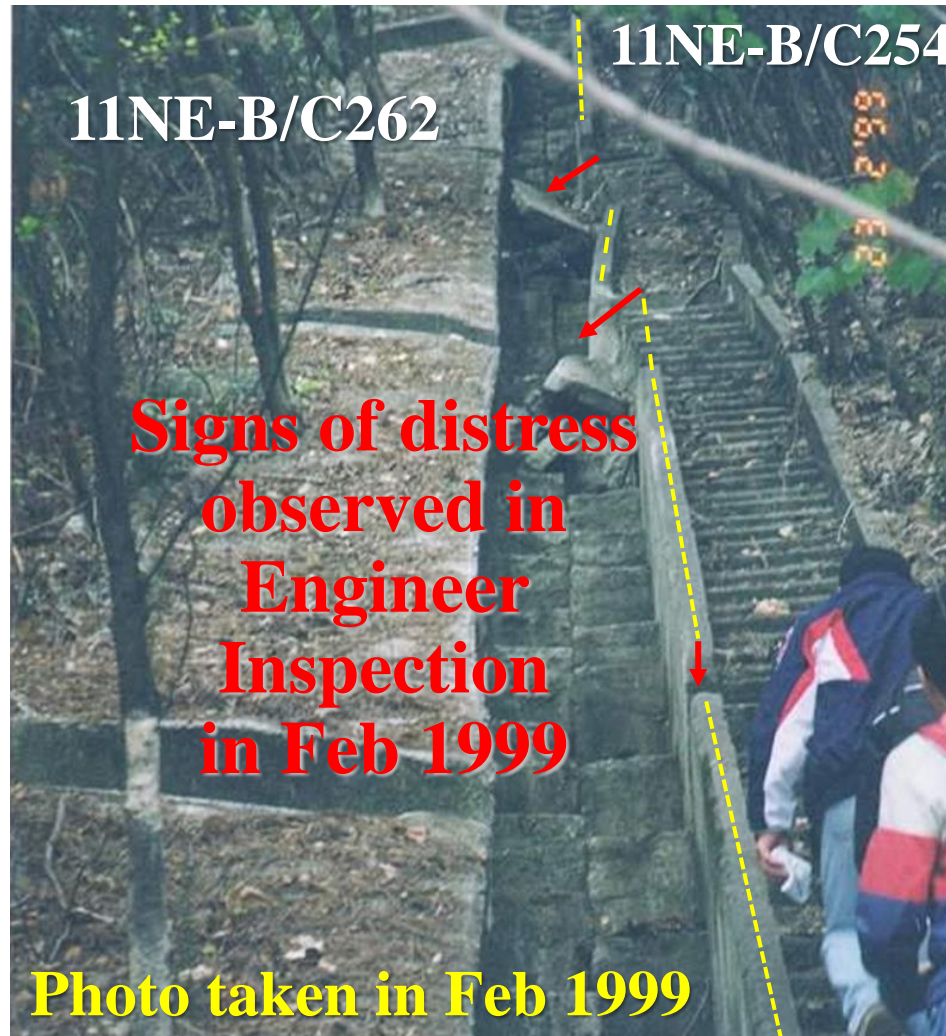
Aug 1999 Tsing Yi Road

(detached 300 m³ + displaced >5000 m³)

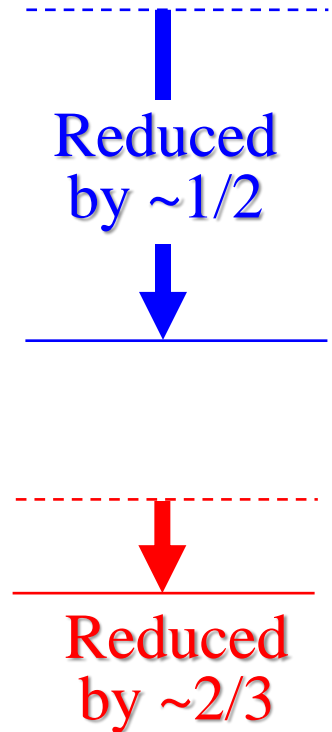
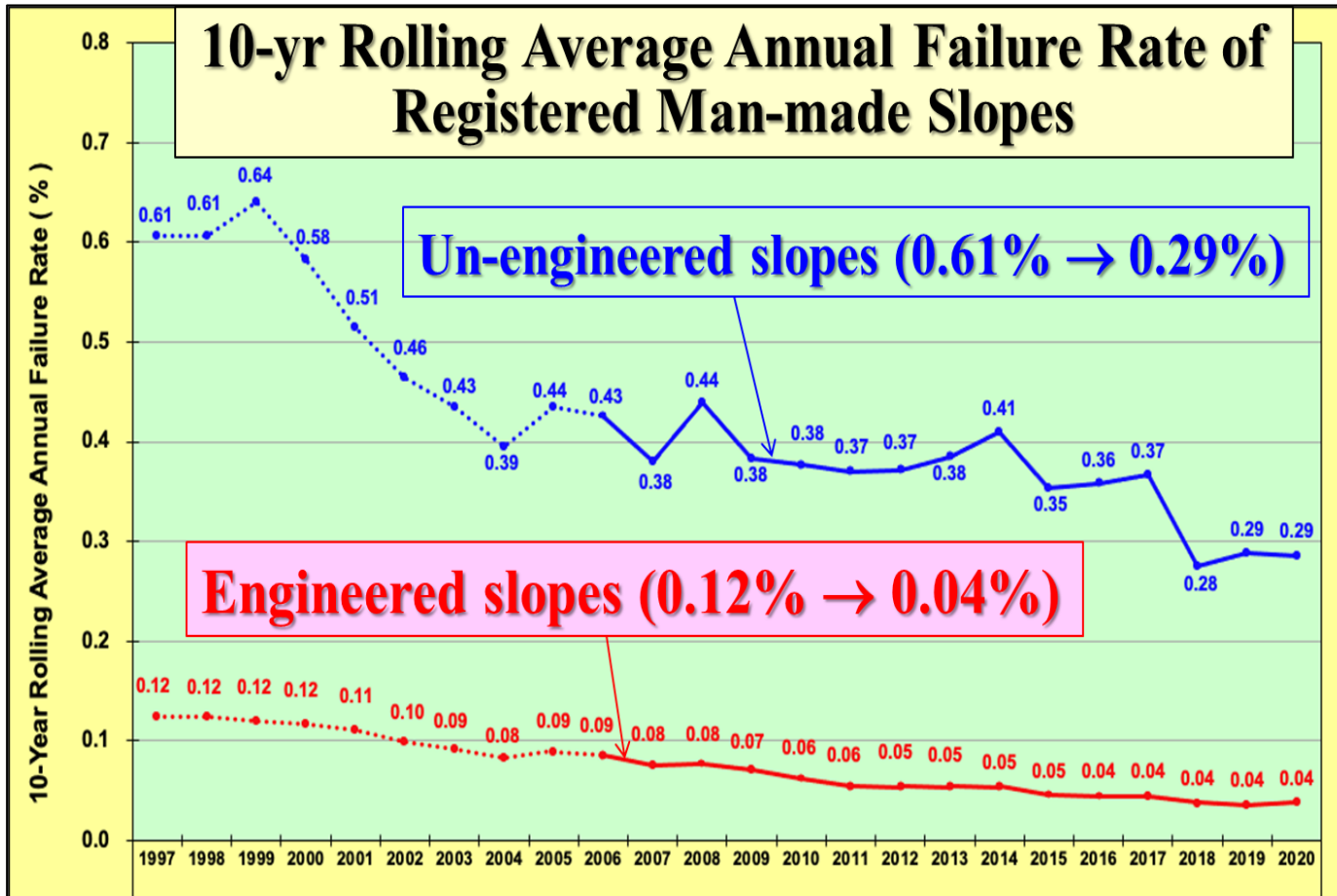


Engineer Inspection & Emergency Response

(reduce consequence, hence risk)



Improvement (1997 to 2020)



Note: 10-yr rolling average adopted to “even out” rainfall effects

(2) Local weakness

(Smaller scale)

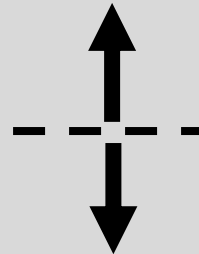
(1) Washout failure

(Mixed)

(3) Major defect

(Larger scale)

Smaller
scale



Larger
scale

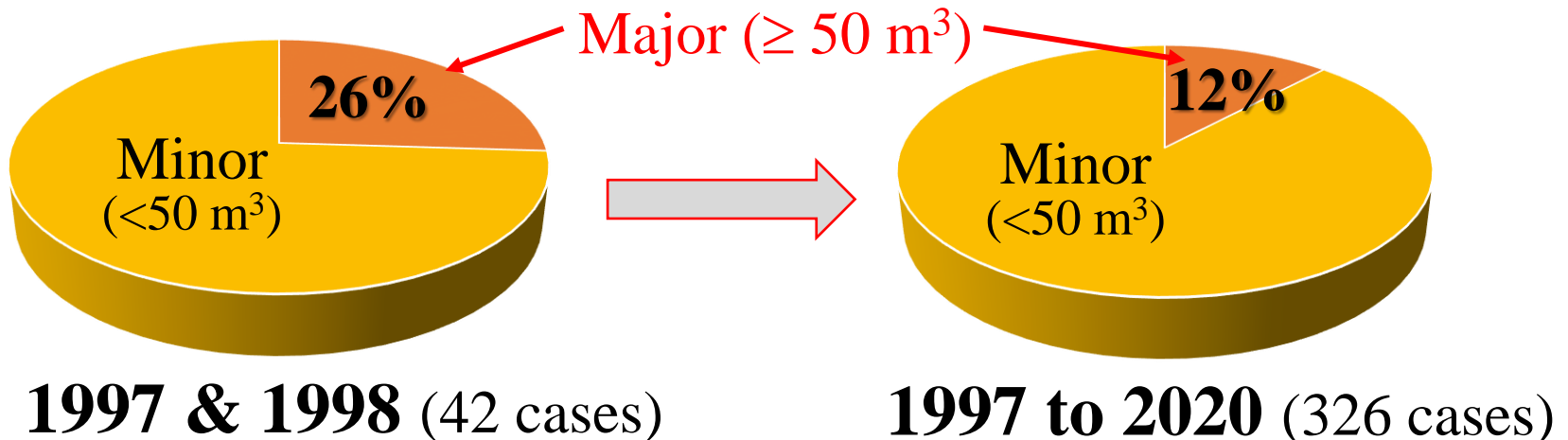
**To minimize, yet
difficult to eliminate**



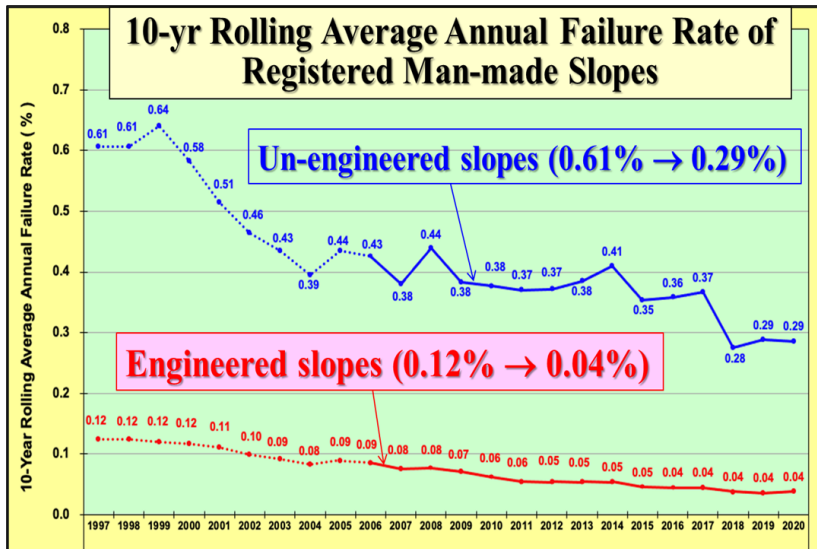
**+ holistic
risk management**



**To avoid
as far as possible**



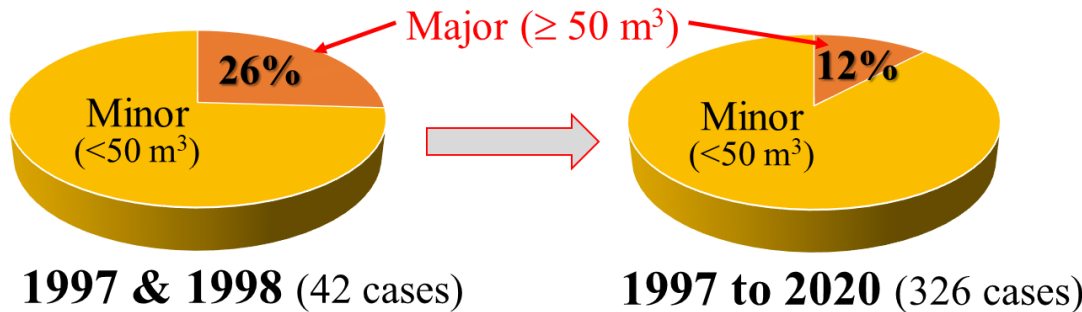
Apparently improved



Reduced by ~1/2

Reduced by ~2/3

Degree of improvement from the figures - Optimistic



Bridging the Gap between Theoretical and Actual Slope Performance

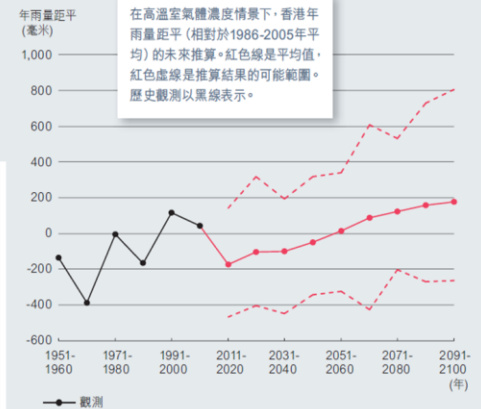
(4) What next ?



More Rain + More Extreme Rainfall

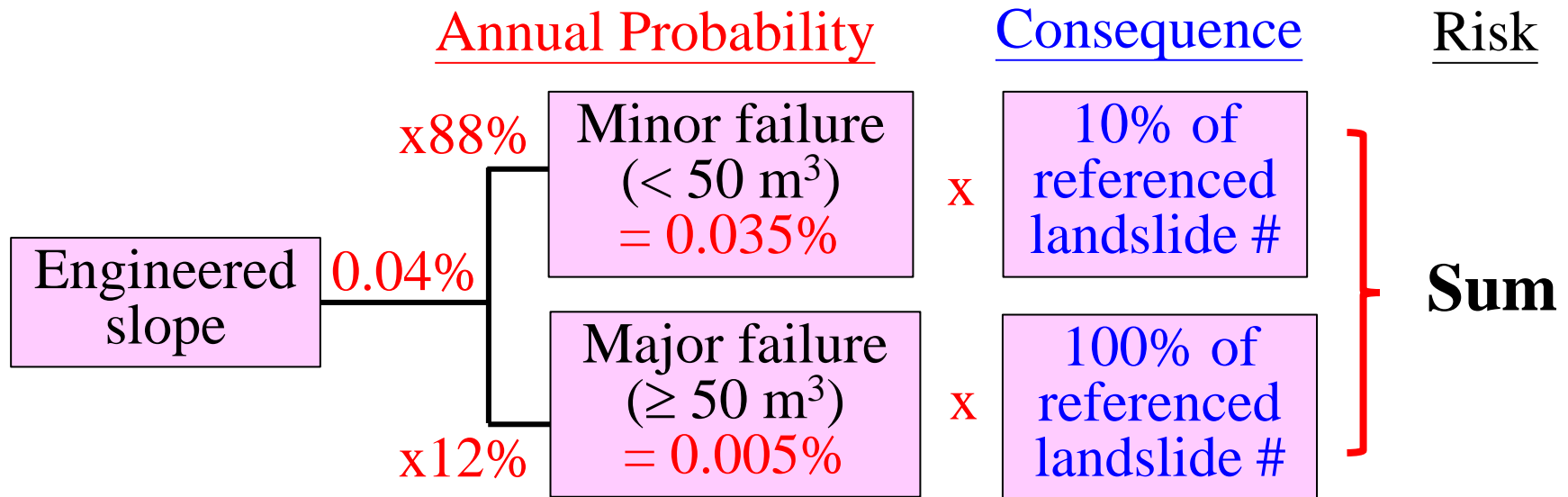
根據IPCC發佈的最新情況，在高溫室氣體濃度情景下，預計香港極端多雨的年份將由1885-2005年間的3年，上升至2006-2100年的12年。此外，在21世紀末的每年降雨量，預計將較1986-2005年的平均降雨量上升約180毫米。極端降雨事件亦會在本世紀增加。

降雨 香港將會更多雨、更多極端降雨



極端降雨
將更頻繁

Overall Risk Assessment



Potential loss of life (PLL) by 50 m³ direct hit (Wong & Ho, 1995)

Facility Group, FG (Example)	Consequence (PLL) #
1 (densely used building; road with very heavy traffic)	3
2 (lightly used building; road with heavy traffic)	1
3 (densely used open space; road with moderate traffic)	0.1
4 (lightly used open space; road with low traffic)	0.01
5 (remote area; road with very low traffic)	0.001

Risk of Engineered Slope Failure, PLL / yr (PLL = Potential Loss of Life)

As Low As Reasonably Practicable (ALARP)

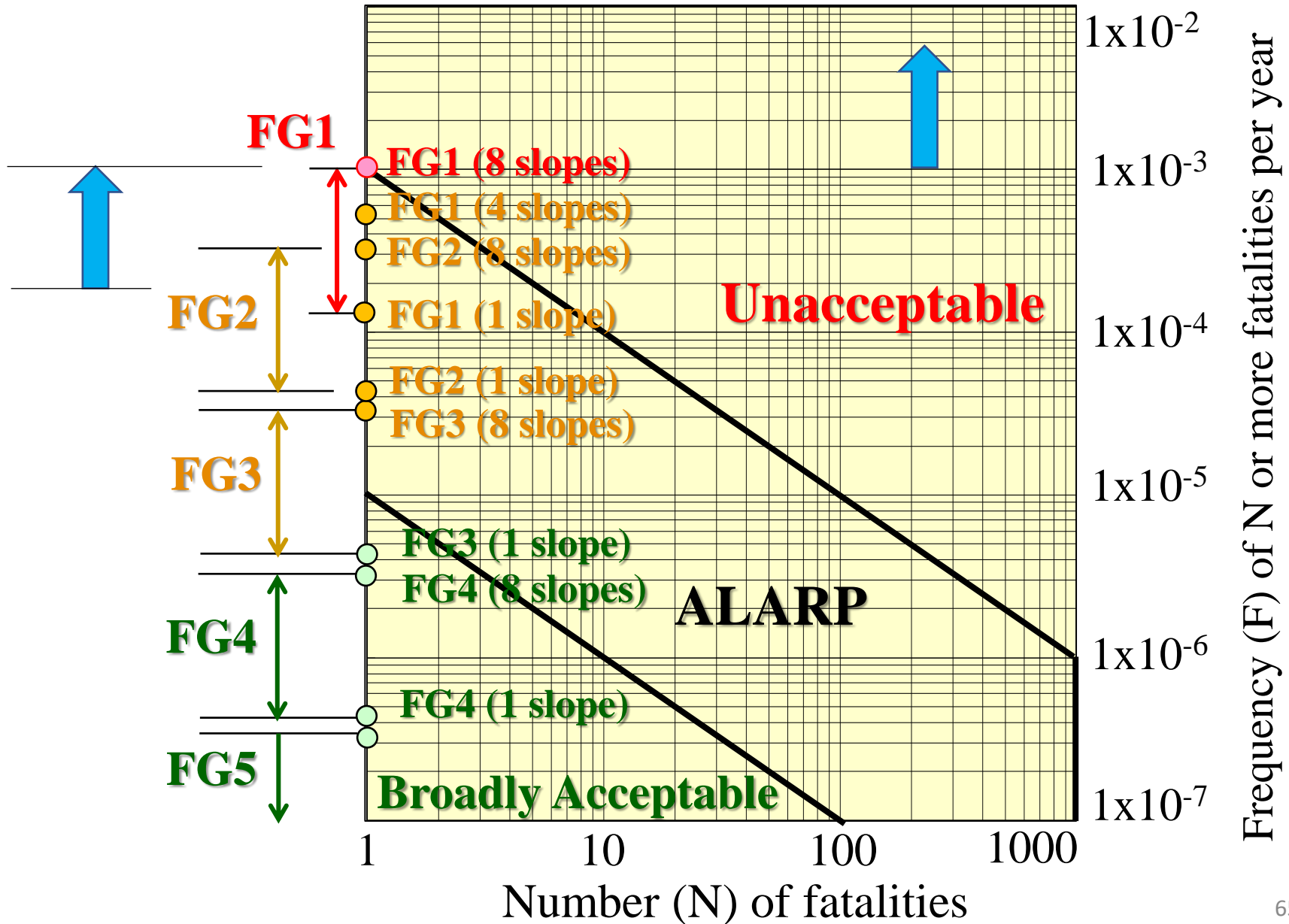
Unacceptable

FG	Risk /Slope	Risk / 500 m long Consultation Zone (PLL per year)			
		1 Slope/Zone	2 Slopes/Zone	4 Slopes/Zone	8 Slopes/Zone
1	2.55×10^{-4}	2.6×10^{-4}	5.1×10^{-4}	1.0×10^{-3}	2.0×10^{-3}
2	8.5×10^{-5}	8.5×10^{-5}	1.7×10^{-4}	3.4×10^{-4}	6.8×10^{-4}
3	8.5×10^{-6}	8.5×10^{-6}	1.7×10^{-5}	3.4×10^{-5}	6.8×10^{-5}
4	8.5×10^{-7}	8.5×10^{-7}	1.7×10^{-6}	3.4×10^{-6}	6.8×10^{-6}
5	8.5×10^{-8}	8.5×10^{-8}	1.7×10^{-7}	3.4×10^{-7}	6.8×10^{-7}

Broadly Acceptable

Note: For landslides in HK,
F at $N \geq 1$ is $\approx \frac{1}{2}$ PLL /yr

Note: Frequency in the late 1990s was ~5 times higher



Way Forward

1. Continue with enhanced practices

- Robust design >> “over precise” calculation
- Holistic risk management >> “zero” failure
- Professional skill >> “standard” procedures

“In the soil engineering world
it is all too easy to spend time
on calculating what can be calculated
rather than on what should be calculated, to giving
an over precise answer to the wrong question ...”
(Lumb, 1980)

2. Enhance drainage

- Launch slope drainage enhancement projects
- Improve drainage design & detailing
- Provide redundancy (give up self-cleansing velocity)

Chai Wan
(Oct 2016)



Ho Man Tin
(Oct 2021)



3. Attend to slopes with severe consequence



- Identify these slopes (“Super” Category 1 – PLL >> 3)
- Call for risk assessment (apart from FOS)
- Require robust design, or risk management measures (e.g. warning system)

4. Communicate risk with stakeholders

➤ Know where we are

Engineered Slope Overall Annual Failure Rate		
Not robust	Not maintained	$> 1.2 \times 10^{-3}$
	Maintained	$\sim 8 \times 10^{-4}$
Average	Maintained	$\sim 4 \times 10^{-4}$
Robust	Maintained	$\leq 4 \times 10^{-5}$

➤ Explain & engage



THE 11TH LUMB LECTURE

Bridging the Gap between Theoretical and Actual Slope Performance

Ir Prof. WONG Hok-ning

6:30 P.M. DECEMBER 3, 2021 (FRIDAY)

RAYSON HUANG THEATRE, THE UNIVERSITY OF HONG KONG



Department of Civil Engineering
The University of Hong Kong

HKIE Geotechnical Division
The Hong Kong Institution of Engineers