Evolution of Natural Terrain Hazard Assessment Strategy in Hong Kong

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Natural Hillside Plan Area 690 km$^2$
Total Land Area 1104 km$^2$

Key Issues with Natural Terrain

- Many landslides in an intense rainstorm
- Increasing risk due to developing closer to natural hillside
- Small failure can have serious consequence
- Low frequency, large magnitude event
Principally Shallow Landslides

Colluvium

Weathered rock

Rock fall

Joint-controlled slide
Some Large-magnitude Events

- 1995 Shum Wan Rd Landslide (26,000 m$^3$): 2 fatalities
- 1924 Pokfulam Rock/Boulder Fall: 5 fatalities
- 1990 Tsing Shan Debris Flow (20,000 m$^3$): Change in land use
Management of Natural Terrain Hazards

- Natural hillside catchment
- Engineering Geology / Geomorphology (API, Field Mapping)
- Mitigation measures (e.g. check dam, flexible barrier)
- Preventive measures (e.g. soil nail, retaining structure)
- Man-made slope
- Remote Sensing
  - Large area extent
  - Dense vegetation
  - Difficult access
  - Difficult to locate features in the field
  - Limited scope for ground investigation
Early Phase of Landslide Studies

**Ad hoc Studies**
- major landslide events

1990 Tsing Shan Debris Flow
- Source volume 350 m$^3$
- Valley colluvium (bouldery)
- Debris volume 20,000 m$^3$
- Runout distance 1 km$^2$
- Travel angle 23° - 24°

Nov 1993 on Lantau Island
- Over 800 landslides
- Shallow failures involving bouldery colluvium
- Terrain gradient 30° to 35°
- Higher debris mobility for CDF than OHF
(2) Territory-wide Landslide Data Compilation & Analysis Phase

Scoping Programme –
Natural Terrain Landslide Study

- Natural Terrain Landslide Inventory (1995)
- Large Landslide Dataset (1998)
- Natural Terrain Susceptibility Analysis (1998)

Systematic Landslide Investigation (since 1997) – provides further insights into the causes, mechanisms and characteristics of notable natural terrain landslides
Natural Terrain Landslide Inventory

- 11,000 recent & 19,000 relict landslides

API of high-flight aerial photographs (>2,400 m)

Large Landslide Dataset

- API of low-flight 1963/64 aerial photographs + some field inspections

- Scarp width >20m 1,900 relict landslides
Natural Terrain Susceptibility Analyses
(Technical Note TN 1/98)

Very High = landslide frequency >100 no./km²
High = landslide frequency 40 - 100 no./km²
Moderate = landslide frequency 20 - 40 no./km²
Low = landslide frequency 10 - 20 no./km²
Very Low = landslide frequency ≤ 10 no./km²

Gradient
Geology
(3) Regional and Site Specific Studies Phase

Development Programme – Consolidation of Knowledge

- Regional Hazard Review – North-easterly Hong Kong Island (2006)
- Site Specific Studies (since 2001)
Regional Study – Tsing Shan Foothills

Main Focus:
key factors controlling NT landslides in Tsing Shan foothills

- Area-based susceptibility analysis 1:2,000 scale
- Landslides/km²: <100 to 400

Study Area: 6.5 km²

Tuen Mun Bypass Construction Site

Year 2000 Landslides (c. 100 on 14.4.2000)
Key Controlling Factors for NT Landslides

Regolith Downslope of Rock Outcrop

Head of Drainage Line

Lithological Boundary
Regional Hazard Review – North-eastern Hong Kong Island

Main Focus: To develop a geomorphological based approach to supplement the landslide based approach

MFJV, 2003
Derivation of Hazards from Engineering Geological Maps

- Potential landslide source area of 'dormant' activity
- Area of 'dormant' activity
- Potential landslide source area from multiple source
- Potential rockfall source area of 'active' activity
- Potential entrainment area comprising 'confined' colluvium
- Potential entrainment area comprising 'distal' colluvium
- Potential entrainment area comprising 'talluvium' or local source area
Design Event Approach

Consequence Class

<table>
<thead>
<tr>
<th>Proximity</th>
<th>Facility Group (GEO Report 68)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 &amp; 2</td>
</tr>
<tr>
<td>Very Close (e.g. AE ≥ 30°)</td>
<td>I</td>
</tr>
<tr>
<td>Moderately Close (e.g. AE ≥ 25°)</td>
<td>II</td>
</tr>
<tr>
<td>Far (e.g. AE &lt; 25°)</td>
<td>III</td>
</tr>
</tbody>
</table>

Design Requirements

<table>
<thead>
<tr>
<th>Susceptibility</th>
<th>Consequence Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely susceptible</td>
<td>Worst Credible Event</td>
</tr>
<tr>
<td></td>
<td>(notional return period 1:1,000)</td>
</tr>
<tr>
<td>highly susceptible</td>
<td>Conservative Event</td>
</tr>
<tr>
<td>moderately susceptible</td>
<td>(notional return period 1:100)</td>
</tr>
<tr>
<td>low susceptibility</td>
<td>Further study not required</td>
</tr>
</tbody>
</table>
Systematic Studies and Mitigation Programme –
50% of the resources under LPMitP (since 2010) for natural terrain vs. 5% on average pre-2010

- Enhanced Natural Terrain Landslide Inventory (2005)
- Inventory of Historical Landslide Catchments (2007)
- Area-based Approach to Natural Terrain Hazard Studies (since 2008)
- Regional Hazard Assessment – West Lantau Island (Out-of-turn LPMit Action, 2009)
Recent landslides (within AP coverage; <100 years) c. 19,000 no.

Enhanced Natural Terrain Landslide Inventory (ENTLI) is updated about every 3 years

In 2005, commenced enhancement of the NTLI (ENTLI) - using high & low-flight AP (<2,400 m) with improved resolution and temporal coverage

Relict landslides c. 90,000 no.
Inventory of Historical Landslide Catchments (HLC) – catchments with ENTLI features that occurred close to important existing facilities

Criterion 1

A landslide crown is within 100 m of the upslope boundary of an important facility

Criterion 2

A landslide toe is within 40 m, or 40% of the trail length, whichever is greater, of the upslope boundary of an important facility

Important existing facilities
- Buildings
- Major transport corridors
Area-based Approach to NTHS

Historical Landslide Catchment (HLC)

Related Catchment (RC) – hillside catchment of similar geological & geomorphological settings to HLC

Study Area – A group of HLC (and RC) affecting an individual unit of existing development
Village House Evacuations

Wang Hang Village

San Tsuen
Nam Chung Tsuen

7.6.2008: Lantau Island c. 2600 landslides

Road Closures

Keung Shan Road

4-hour rainfall isohyets & landslide distribution
Regional Hazard Assessment (West Lantau Island)

- Develop a methodology for prioritisation and selection of hillsides requiring hazard mitigation works
- Ranking of hillside catchments and selection of catchments for follow up mitigation works

Legend
- Study area (18.5 km²)
- Villages
- Main Roads
(5) Technical Development

In support of natural terrain studies

- Soil Bioengineering
- Geotechnical Instrumentation & Monitoring
- Age Determination of NT Landslides
- Remote Sensing Technology
Soil Bioengineering

- Live cut branches &/or rooted woody plant materials
- Native vegetation around installation areas
- Specifically select & arrange to assist in controlling: shallow mass movement, water collection & transport, and surface erosion

Guidelines for Soil Bioengineering Applications on Natural Terrain Landslide Scars (GEO Report No. 227)

Maunsell, 2004 – 2006
Rehabilitation of Shotcreted Landslide Scars
(to be implemented in 2014/15)
Geotechnical Instrumentation & Monitoring
– for improved understanding of ground & groundwater behaviour

- Translational, Rotational & Settlement Sensor
- Water Content TDR
- Piezometer
- Inclinometer
- Jet-fill Tensiometer
- Crackmeter
- DGPS

ARUP, 2008 – 2011
Geotechnical Monitoring of Distressed Hillsides (to be installed in 2014/15)

Landslide Complex at Tai O Cemetery

Keung Shan Road
Age Determination of NT Landslides

- Direct dating of relict NT landslides (GEO Report No. 170):
  - Radiocarbon ($^{14}$C) – c. 200 to c. 50,000 years BP
  - Optically Stimulated Luminescence (OSL) – c. 100s to 100s of thousands years BP
  - Cosmogenic nuclide (Be$^{10}$, Al$^{26}$) – c. 2,000 to c. 1 million years BP

- Quantitative framework for improvements to design events – relevance of large relict landslides to present day climatic conditions

- Relationships between climate change and large landslides
Landslide Age/Volume Relationships of Large Landslides and Rockfalls (OSL & Cosmogenic Nuclide methods)

Site ID:
ALC = Ap Lei Chau
FNS = Fei Ngo Shan
LCR = Lai Cho Road
LLU = Lo Lau Uk
LR = Lion Rock
ML = Mid-levels
NS = Nam Shan
PH = Pat Heung
PO = Pui O
SPW = Sunset Peak West
STW = Sai Tso Wan
SW = Sham Wat
TCE = Tung Chung East
TO = Tai O
TSB = Tsing Shan B
TSC = Tsing Shan C
TY = Tsing Yi
WCY = Wong Chuk Yeung
WLH = Wong Lung Hung

No. of Numerical Ages = 99

Landslide Types:
- Deep-seated
- Rock Fall
- Open Hillside

Age (x 1000 Years)

- 52.2 ± 6.1 ka ($\chi^2 / v = 2.70$)
- 28.4 ± 2.4 ka ($\chi^2 / v = 3.93$)
- 15.2 ± 2.9 ka ($\chi^2 / v = 2.99$)
- 7.0 ± 0.7 ka ($\chi^2 / v = 0.68$)
- 4.0 ± 0.5 ka ($\chi^2 / v = 11.81$)
# Remote Sensing Technology for NT Studies

<table>
<thead>
<tr>
<th>Position</th>
<th>Terrestrial</th>
<th>Air-borne</th>
<th>Space-borne (satellite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data (Status)</td>
<td><a href="image">Image Photogrammetry (Routine)</a></td>
<td><a href="image">Image LiDAR (Mobile)</a></td>
<td><a href="image">Image Satellite</a></td>
</tr>
<tr>
<td><strong>Image (Photogrammetry)</strong> (Routine)</td>
<td><img src="image" alt="Image Photogrammetry" /></td>
<td><img src="image" alt="Image LiDAR" /></td>
<td><img src="image" alt="Image Satellite" /></td>
</tr>
<tr>
<td><strong>Radar (InSAR)</strong> (Development)</td>
<td><img src="image" alt="Image Radar" /></td>
<td><img src="image" alt="Image InSAR" /></td>
<td><img src="image" alt="Image Satellite" /></td>
</tr>
<tr>
<td><strong>Laser (LiDAR)</strong> (Mainstream)</td>
<td><img src="image" alt="Image Laser" /></td>
<td><img src="image" alt="Image Mobile LiDAR" /></td>
<td><img src="image" alt="Image Satellite" /></td>
</tr>
</tbody>
</table>
Digital Technology - Airborne LiDAR survey
(Virtual Deforestation)

1st return from tree top
2nd return from branches
3rd return from ground

LiDAR point cloud
3D terrain (feature mapping)

Digital Elevation Model – Debris Mobility Modeling
(6) Refinement to Current Practice

Enhance current practice and address lessons learnt

- Enhanced Approach for Dealing with NTHS
- HLC Selection Criteria
- Potentially Problematic Hillside Pockets
- Sizeable Catchments with Major Drainage Lines
Enhanced Approach for NTHS
(TGN 36, TGN 37 & TGN 38)

- Introduce Topographic Depression (TD) Catchments
- Application of R-t-K-H principle to individual catchments
- Streamline the Design Event Approach (replace ‘Worst Credible Event’ and ‘Conservative Event’ by a ‘Design Event’)
- Clarify the intended level of hazard mitigation
- Adopt a new set of rheological parameters for analytical design of mitigation measures for TD Catchments
- Enhance and extend the application of prescriptive barriers to mitigation of open hillslope landslides affecting buildings
## Level of Hazard Mitigation

<table>
<thead>
<tr>
<th>Facility affected</th>
<th>Level of Hazard Mitigation Required</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hazards from CD/TD catchments</td>
<td>For OH Catchments: Empirical design based on use of prescriptive barriers where the qualifying criteria are satisfied (TGN 37) (Note: if not, designed by analysis)</td>
</tr>
<tr>
<td></td>
<td>Hazards from OH catchments</td>
<td>Analytical design of mitigation measures to cater for Design Event</td>
</tr>
<tr>
<td>Group 1 &amp; 2 (high consequence)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Group 3 (moderate consequence)</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
HLC Selection Criteria

Runout distance of debris flows that occurred in June 2008 vs. those recorded in the ENTLI

<table>
<thead>
<tr>
<th>Runout distance of debris flow</th>
<th>No. of cases recorded in the ENTLI (up to 2006)</th>
<th>No. of cases identified in Lantau Island (June 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runout ≥200 m</td>
<td>162</td>
<td>105</td>
</tr>
<tr>
<td>Runout &gt;200-500 m</td>
<td>149</td>
<td>87</td>
</tr>
<tr>
<td>Runout &gt;500-1000 m</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Runout &gt;1000 m</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

For DF catchments, extend the plan distance between the landslide crown and the upslope boundary of the facility from 100 m to 200 m.
Potentially Problematic Hillside Pockets

Sizeable Catchments with Major Drainage Lines

Small tracts of hillsides flanking developed areas – both types of hillside may deserve LPMit actions

Potential locations of low-frequency, large-magnitude debris flows affecting high consequence facilities
Concluding Remarks

- Natural terrain landslides occur as part of the natural landform evolution ⇒ involves considerable uncertainties
- Our technical knowledge and capability in tackling natural terrain hazards are still fairly limited
- Some circumstances, such as climate change, are not entirely within our comprehension or control
- There will be a need to review and enhance the current practice as knowledge and experience develops

Thank You