Debris Flow Modelling

Stuart Millis
Senior Engineering Geologist
Ove Arup & Partners Hong Kong Limited

Debris Flows

• A landslide in which the landslide debris moves by the dominant mechanism of slurry flow. (GEO, 2003)
• Constitute one of the biggest natural terrain hazards due to their high mobility and impact forces
• Therefore need to be able to assess the likely run-out path and distance in order to define the vulnerability of facilities at the catchment toe.
Some Notable Examples of Debris Flows

- Tsing Shan
- Sham Tseng San Tsuen
- Lei Pui Street
- Fei Ngo Shan
- 7 June 2008 landslides on North Lantau

Tsing Shan – September 1990
• Source Volume – 2,000m³ (initiated by a trigger failure of a few 100’s m³)
• Total Volume Involved – 19,000m³
• Angle of Reach 21°
• Estimated landslide velocities of 16.5 m/s
• Massive Entrainment of Debris
• Catchment had high Channelisation Ratio
• Occurred during unexceptional rainstorm (136mm in 5 hours & return period <2 years)

Tsing Shan – September 1990

Sham Tseng San Tsuen – August 1999
Sham Tseng San Tsuen – August 1999

- 1 Fatality
- Multiple Source Areas
- Main Source Area – 600m³
- Maximum Active Volume in drainage line – 480m³
- Travel Angle 24°
- Catchment had an extremely high Channelisation Ratio
- Little to no entrainment of debris
- Occurred during rainstorm with a return period of 49 years

Lei Pui Street – September 2001
- Source Volume – 250m³
- Maximum Active Volume – 780m³
- Travel Angle 23°
- Peak landslide velocity of about 14 m/s
- Entrainment exacerbated due to source debris cascading over cliff
- Started as open slope failure but became channelised in lower portion
- Catchment had moderate Channelisation Ratio
- Rainfall return period of 14 years

Lei Pui Street – September 2001

Fei Ngo Shan – August 2005
• Source Volume – 3,350m³
• Very limited entrainment of additional material with Total Volume of about 4,025m³
• Travel Angle 22°
• Peak landslide velocity of about 19 m/s
• Started as open slope failure but became channelised in mid-to-lower portion
• Catchment had moderate Channelisation Ratio
• Rainfall return period of about 50 years
• Source Volume ≈3,000 m³
• Additional debris entrainment within drainage channel
• Started as open slope failure just above the head of a drainage line
• Catchment had high Channelisation Ratio
• Resulted in road closure for several months
• Rainfall return period of about 1,000 years
• Currently undergoing detailed study
Key Stages in Debris Flow Modelling

- Software selection
- Building a site-specific database (back analysis)
- Review of other similar sites (if no site-specific back analysis can be conducted)
- Identification of Landslide Source Areas
- Determination of Debris Flow Paths
- Selection of Rheological Models
- Debris Flow Modelling

Empirical Approach

- Angle of Reach Approach
  - Typically assessed based on area specific case histories

\[ \alpha = \text{fahrböschung (Travel Angle)} \]
Empirical Approach

- Relatively crude approach
- Useful for Initial Screening Stage but now largely superseded by Analytical Software for detailed studies

Analytical Software

- GEO DMM
  - Spreadsheet format model developed by the GEO
  - Pseudo three-dimensional analysis
  - Available from GEO for work on Government Projects
Analytical Software

• DAN-W
  • Commercial software developed by Oldrich Hungr
  • Pseudo three-dimensional analysis
  • Available from http://www.clara-w.com/DANWRunoutAnalysis.html

Analytical Software

• Flo-2D
  • Two-dimensional (plan view) commercial software designed primarily for Flood Risk Assessment
  • Also found to model well highly saturated debris flows / floods
  • Available from http://www.flo-2d.com/index.htm
Site Specific Databases – Back Analysis

• Key information needed for Back Analysis:
  • Landslide source location
  • Landslide source volumes
  • Debris flows path – vertical elevation, width and extent
  • Mass balance of landslide
  • Landslide rheology – open hillslope or channelised debris flow?
  • If possible, landslide superelevation at various points along run-out trail to allow velocity calculation

• Information primarily gathered from Field Mapping (recent failures) and historical records such as GEO Landslide Investigation Reports

Input Data – Source & Vertical Profile
**Input Data – Debris Path & Mass Balance**

- **Record details of the Channel Profile**
  - Long-section along entire length
  - Series of channel cross-sections
  - Nature and thickness of any debris within channel base / levees

- **Estimate the Channelisation Ratio**
  - Width (W) to Depth (D) Ratio of the Cross-section
  - Channelisation typically occurs at <5 (Hungr, 1984)

---

**Input Data – Debris Path & Mass Balance**

- **Record debris entrainment and deposition thickness along the run-out trail**
Input Data – Debris Path & Mass Balance

- As well as cross sectional profiles of channel and debris along the channel length

<table>
<thead>
<tr>
<th>Week</th>
<th>Channel</th>
<th>Year</th>
<th>Section</th>
<th>Debris</th>
<th>Elliptical</th>
<th>Superelevation</th>
<th>Mass Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>2100</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>2100</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>2100</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>2100</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>2100</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Velocity check for back analysed failures based on the Superelevation (Johnson & Rodine, 1984)

- Allows comparison of actual v’s computed velocity

\[
\begin{align*}
\text{For channels with gradients } & \leq 15^\circ \text{ to the horizontal:} \\
\hat{u} &= (g + \frac{\beta}{2} \cos \delta \sin \Psi)^{1/2} \\
\text{For channels with gradients } & > 15^\circ \text{ to the horizontal:} \\
\hat{u} &= (g + \frac{\beta}{\cos \Psi})^{1/2}
\end{align*}
\]

where:
- \( \hat{u} \) = mean velocity
- \( g \) = acceleration due to gravity
- \( \Psi \) = radius of curvature
- \( \delta \) = gradient of the channel
- \( \beta \) = angle of superelevation
Input Data – Debris Path & Mass Balance

Selection of Rheological Model

- **Frictional Model**
  
  \[ T = A_h \gamma H_i (\cos \theta + a_c / g)(1 - r) \tan \phi \]

  - Suitable for modelling open hillslope Debris Flows with moderate saturation

- **Voellmy Model**
  
  \[ T = A_d \left[ \gamma H_i (\cos \theta + a_c / g) \tan \phi + \gamma \tau_1 / \tau \right] \]

  - Suitable for modelling:
    - Channelised Debris Flows
    - Highly saturated open hillslope Debris Flows / Floods
Selection of Rheological Model

• Most Channelised Debris Flows initiate from open hillslope sources
• More than one model may be required for a single landslide
• Not all software packages allow this to be modelled

Site Specific Databases

• Dependant on the number of past failures within, or in close proximity, to the study site
• Some sites are better suited to this than others....
Debris Flow Modelling – Building the Model

- Run-out Path Long Section
- Run-out Path Width / Profile

Key Variable to Assess Debris Mobility

often similar to the Travel Angle of the Landslide
Debris Flow Modelling – Building the Model

Key Variables to Assess Debris Mobility

The higher this number is, the more ‘liquid’ the flow becomes

Debris Flow Modelling – Running the Model
Maximum observed run-out of landslide
Maximum observed run-out of landslide
Maximum observed run-out of landslide
Maximum observed run-out of landslide
Model Checking / Calibration

- Debris distribution

**Volume Estimates from Field Mapping**

<table>
<thead>
<tr>
<th>0</th>
<th>13</th>
<th>23</th>
<th>33</th>
<th>43</th>
<th>53</th>
<th>63</th>
<th>73</th>
<th>83</th>
<th>93</th>
<th>103</th>
<th>113</th>
<th>123</th>
<th>133</th>
<th>143</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulked Volume (m$^3$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3540</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>850</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>285</td>
<td>170</td>
<td>885</td>
<td></td>
<td>655</td>
<td>945</td>
<td>510</td>
<td>215</td>
<td>70</td>
<td>110</td>
<td>120</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3715</td>
<td>3570</td>
<td>2605</td>
<td></td>
<td>3801</td>
<td>1085</td>
<td>573</td>
<td>360</td>
<td>330</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Debris Thickness Estimates from Run-out Modelling**
Model Checking / Calibration

- Landslide velocity
  ![Velocity Estimates from Debris Mobility Modelling](image1)
  ![Velocity Estimates from Superelevation](image2)

Model Checking / Calibration

- Landslide duration (not often available….)
  ![Landslide Duration Graph](image3)
Back Analysis

• Analyse as many ‘local’ failures as possible to build a site-specific database of modelling parameters

<table>
<thead>
<tr>
<th>Landslide No.</th>
<th>Model Type</th>
<th>Landslide Volume</th>
<th>Length of Run-out Trail</th>
<th>Modeled Bulk Friction Angle</th>
<th>Travel Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Frictional</td>
<td>48.5</td>
<td>44</td>
<td>34.5</td>
<td>32.8</td>
</tr>
<tr>
<td>3</td>
<td>Frictional</td>
<td>32.4</td>
<td>49</td>
<td>33</td>
<td>28.7</td>
</tr>
<tr>
<td>9</td>
<td>Frictional</td>
<td>130.9</td>
<td>105</td>
<td>32.3</td>
<td>28.9</td>
</tr>
<tr>
<td>10</td>
<td>Frictional</td>
<td>404.5</td>
<td>200</td>
<td>29.3</td>
<td>28.3</td>
</tr>
<tr>
<td>L502/08</td>
<td>Frictional</td>
<td>202.9</td>
<td>110</td>
<td>32.7</td>
<td>27.2</td>
</tr>
<tr>
<td>L503/08</td>
<td>Frictional</td>
<td>181.3</td>
<td>95</td>
<td>30.5</td>
<td>28.2</td>
</tr>
<tr>
<td>L504/08</td>
<td>Frictional</td>
<td>98.7</td>
<td>103</td>
<td>28</td>
<td>28.7</td>
</tr>
</tbody>
</table>

Back Analysis

• These then form the basis for sensitivity analysis of potential landslide run-out scenarios:
  • Upper Bound – 34.5 degrees
  • Average – 31.5 degrees
  • Lower Bound – 28 degrees
Alternatives to Back Analysis

- For sites with no or limited cases for back analysis:
  - Refer to published guidelines such as Figure 21 of GEO Report 104
    *Note: this may result in a somewhat conservative assessment*
  - Review past studies and published data for other sites in the vicinity of the site in order to develop the range of sensitivity analysis based on sound engineering judgement
    i.e. Ayotte & Hungr, 1998
    GEO Report 174
    Landslide Investigation Reports etc.

Alternatives to Back Analysis

- Empirical correlations of Travel Angle and Source Volume (GEO Report 174)
Modelling Potential Landslide Hazards

- Identification of probable source areas
  - Based upon the hazard model developed for the site

- Determination of debris run-out path
  - Typically developed in GIS using a flow path analysis tool
  - Assessment will only be as good as the survey data used for the Digital Terrain Model

Flow path Assessment for Luk Keng NTHS
Modelling Potential Landslide Hazards

- Determination of probable debris flow width
  - Based upon field mapping and judgement
  - Include allowance for all entrainable material

- Estimation of Channel Yield Rate (Y) to determine entrainable volume
  - Quantity of debris in m$^3$ per m of path length removable by a debris flow (Hungr, 1984)
  - Channel divided into segments ("reach")s of approximately similar character in order to estimate

\[ V_i = Y_i \cdot d_i \cdot W_i \]

Incremental volume for reach 'i':
Modelling Potential Landslide Hazards

• Build analytical model

Debris remains confined within hillside area and doesn’t affect any down slope facilities

Modelling Potential Landslide Hazards

• Conduct Sensitivity Analysis

  • Upper Bound Case
Modelling Potential Landslide Hazards

• Conduct Sensitivity Analysis
  • Worst Case

Nearly all of the debris reaches the toe of the hillside and could thus affect any facilities/people using that area.

Modelling Potential Landslide Hazards
Modelling Potential Landslide Hazards

- Check findings against correlations of Travel Angle and Source Volume (GEO Report 174)

Using the Modelling Data

- Insert ‘Observation Point’ at probable location of any Hazard Mitigation Works
- Use this data to determine impact forces and debris thickness / vertical run-up distance (GEO Report 104 refers)
Future Advances

• Use of LiDAR data for better definition of slope / channel morphology

Future Advances

• Development and application of three-dimensional modelling software
Some Useful References

• GEO Report 104 (2000) Review of Natural Terrain Landslide Debris Resisting Barrier Design + other GEO Reports:


• Hungr & Evans (1997) A Dynamic Model for Landslides with Changing Mass

• Ko & Kwan (2006) Application of Debris Mobility Modeling in Landslide Risk Assessment in Hong Kong

• Kwan & Ko (2008) Mobility Assessment of Debris Floods – Recent Advancement

• Ayotte & Hungr (1998) Run-out Analysis of Debris Flows and Debris Avalanches in Hong Kong

Thank You