Debris Flow Modelling

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

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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.

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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

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Tsing Shan – September 1990

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- **Source Volume – 2,000m³** (initiated by a trigger failure of a few 100's m³)
- **Total Volume Involved – 19,000m³**
- **Angle of Reach 21º**
- **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

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Sham Tseng San Tsuen – August 1999

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- 1 Fatality
- Multiple Source Areas
- Main Source Area – 600m^3
- Maximum Active Volume in drainage line – 480m^3
- Travel Angle 24^o
- Catchment had an extremely high Channelisation Ratio
- Little to no entrainment of debris
- Occurred during rainstorm with a return period of 49 years

Sham Tseng San Tsuen – August 1999

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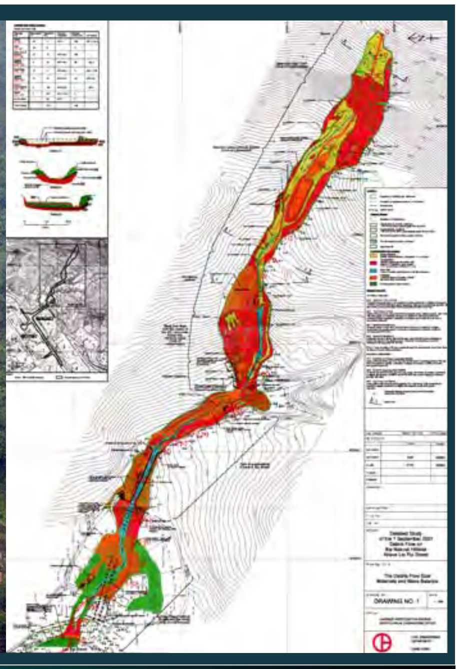

Lei Pui Street – September 2001

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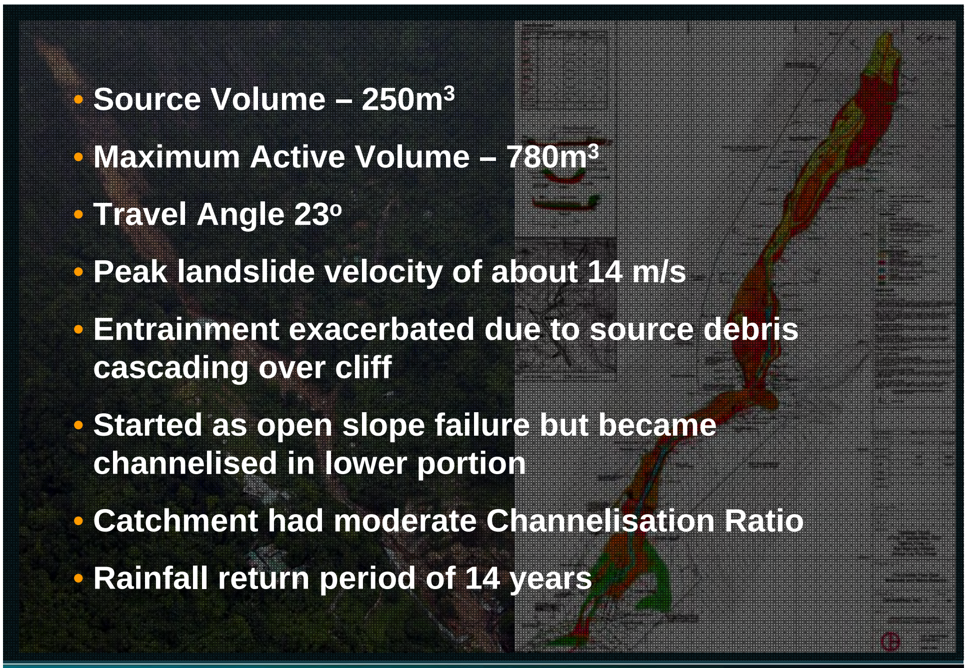

Lei Pui Street – September 2001 ARUP

Fei Ngo Shan – August 2005 ARUP

- Source Volume – 3,350m^3
- Very limited entrainment of additional material with Total Volume of about 4,025m^3
- Travel Angle 22^o
- 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

Fei Ngo Shan – August 2005

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Yu Tung Road, N. Lantau – 7 June 2008

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- Source Volume ≈3,000m^3
- 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

Yu Tung Road, N. Lantau – 7 June 2008

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North Lantau – 7 June 2008

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North Lantau – 7 June 2008

North Lantau – 7 June 2008

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

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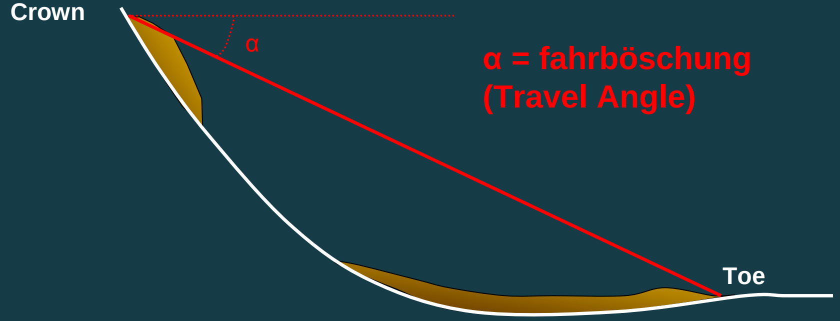
Empirical Approach

- Angle of Reach Approach



- Typically assessed based on area specific case histories

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Empirical Approach

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

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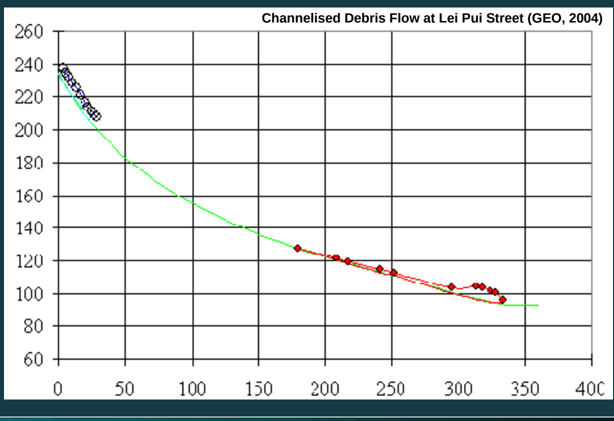
Analytical Software

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



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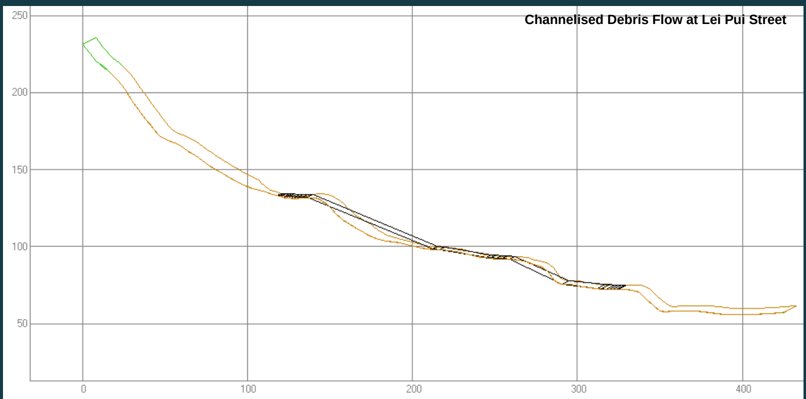
Analytical Software

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



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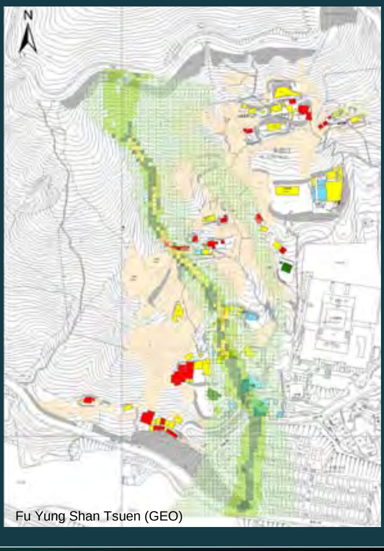
Analytical Software

- **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**



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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**

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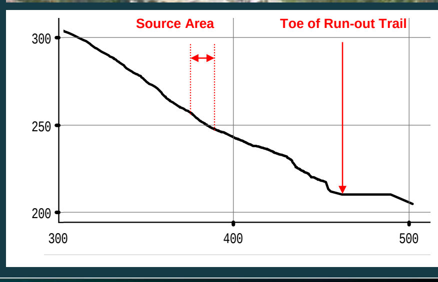
Input Data – Source & Vertical Profile



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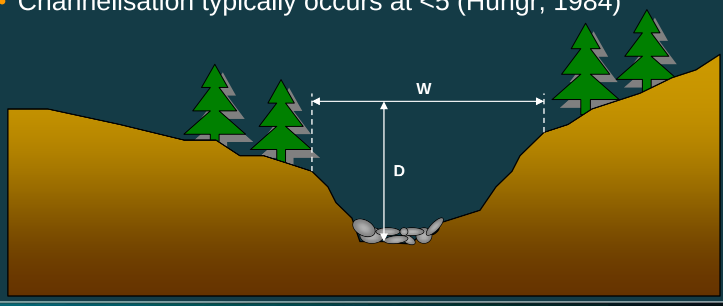
Input Data – Debris Path & Mass Balance

- **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)



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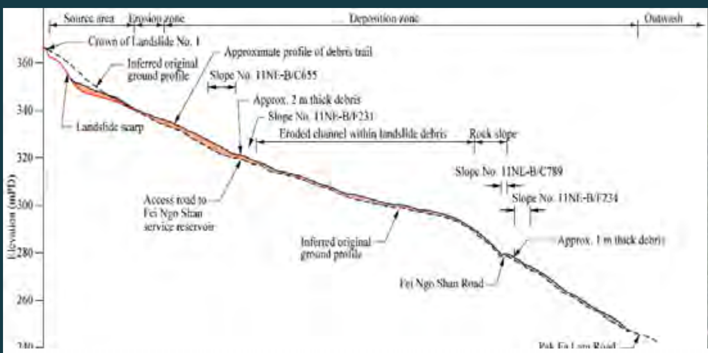
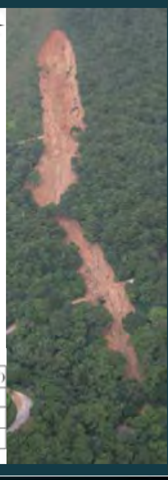
Input Data – Debris Path & Mass Balance

- **Record debris entrainment and deposition thickness along the run-out trail**



Chainage (m)	0–13	13–42	42–53	53–91	91–95	95–106	106–145	145–170	170–208	208–224	224–228	228–260	260–282	282–288
Bulked Volume (m^3)	3850#													
Erosion (m^3)		150	25											
Deposition (m^3)		285	170	885	200	455	945	510	215	30	100	110	100*	12
Mass Balance (m^3)		3715	3570	2685	2485	2030	1085	575	360	330	230	120	20	8

* denotes outwash # denotes Bulked volume = source volume x 1.15



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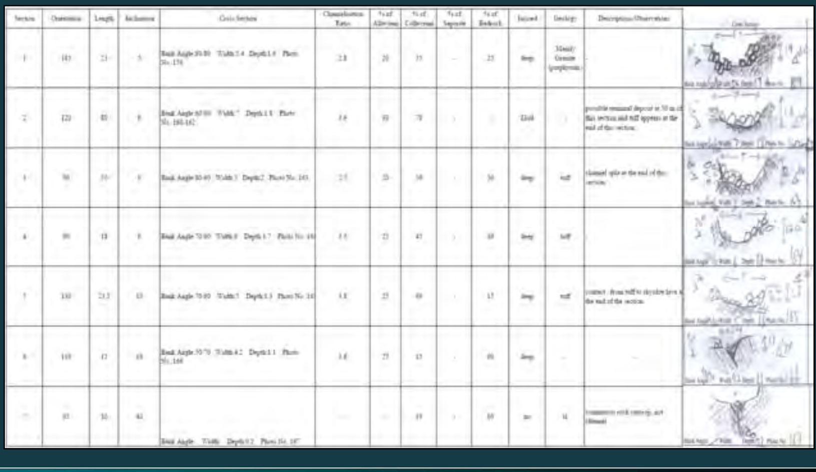
Input Data – Debris Path & Mass Balance

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



Input Data – Debris Path & Mass Balance

- **Velocity check for back analysed failures based on the Superelevation (Johnson & Rodine, 1984)**
- **Allows comparison of actual v's computed velocity**

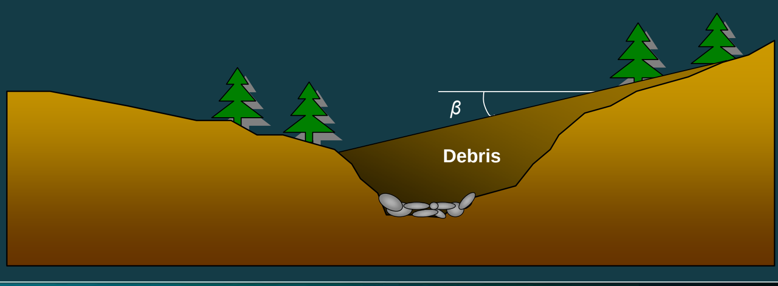
For channels with gradients >15° to the horizontal:

$$\bar{w} = [g \times \Psi \cos \delta \tan \beta]^{1/2}$$

For channels with gradients <15° to the horizontal:

$$\bar{w} = [g \times \Psi \tan \beta]^{1/2}$$

where: $\bar{w}$ = mean velocity
g = acceleration due to gravity
Ψ = radius of curvature
δ = gradient of the channel
β = angle of superelevation



Input Data – Debris Path & Mass Balance

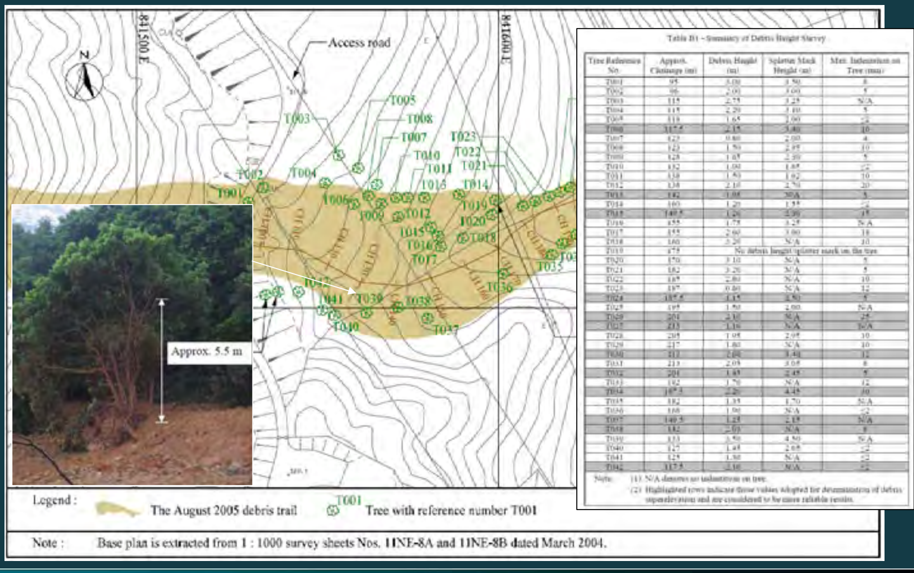


Table B1 – Summary of Debris Height Survey

Tree Reference No.	Approx. Chainage (m)	Debris Height (m)	Splatter Mark Height (m)	Max. Indentation on Tree (mm)
T001	95	3.00	3.50	8
T002	96	2.00	3.00	5
T003	115	2.75	3.25	N/A
T004	115	2.20	3.10	5
T005	118	1.65	2.00	≤2
T006	117.5	2.15	3.40	10
T007	123	0.80	2.00	4
T008	123	1.50	2.85	10
T009	128	1.85	2.50	5
T010	132	1.00	1.85	≤2
T011	138	1.50	1.62	10
T012	138	2.10	2.70	20
T013	142	1.08	N/A	5
T014	160	1.20	1.55	≤2
T015	149.5	1.26	2.30	15
T016	155	1.75	3.25	N/A
T017	155	2.60	3.00	18
T018	160	2.20	N/A	10
T019	175	No debris height/splatter mark on the tree		
T020	170	3.10	N/A	5
T021	182	3.20	N/A	5
T022	185	2.80	N/A	10
T023	197	0.80	N/A	12
T024	185.5	3.15	3.50	5
T025	195	1.50	2.00	N/A
T026	201	2.10	N/A	25
T027	203	1.16	N/A	N/A
T028	205	1.95	2.95	10
T029	217	1.80	N/A	10
T030	212	2.00	3.40	12
T031	213	2.05	3.05	8
T032	201	1.45	2.45	5
T033	192	1.70	N/A	12
T034	187.5	2.20	4.45	30
T035	182	1.35	1.70	N/A
T036	168	1.90	N/A	≤2
T037	149.5	1.25	2.15	N/A
T038	142	2.05	N/A	8
T039	133	3.50	4.50	N/A
T040	127	1.45	2.65	≤2
T041	125	1.30	N/A	≤2
T042	117.5	2.10	N/A	≤2

Note: (1) N/A denotes no indentation on tree.
(2) Highlighted rows indicate those values adopted for determination of debris superelevation and are considered to be more reliable results.

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Selection of Rheological Model

- **Frictional Model**

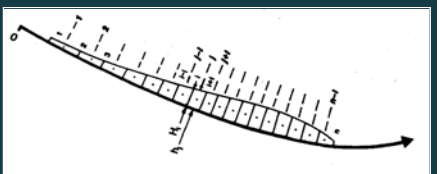
$$T = A_i \gamma H_i (\cos\theta + a_c / g) (1 - r_u) \tan\varphi$$

  - Suitable for modelling open hillslope Debris Flows with moderate saturation

- **Voellmy Model**

$$T = A_i [\gamma H_i (\cos\theta + a_c / g) \tan\varphi + \gamma v_i^2 / \xi]$$

  - Suitable for modelling:
    - Channelised Debris Flows
    - Highly saturated open hillslope Debris Flows / Floods



where: a_c = centrifugal acceleration = v_i^2 / R
R = vertical curvature radius of path
r_u = pore-pressure coefficient = ratio of pore pressure to total normal stress at base of boundary block
φ = friction angle
ξ = turbulence coefficient
A_i = boundary block base area = $ds\ B_i$
γ = unit weight of the boundary block = $\rho\ g$
ρ = bulk density of the flow material
H = flow depth normal to base
B = channel width
ds = infinitesimal length of boundary block
θ = angle of base from horizontal
T = resisting shear force on base
P = tangential internal pressure
v = mean flow velocity

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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

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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….

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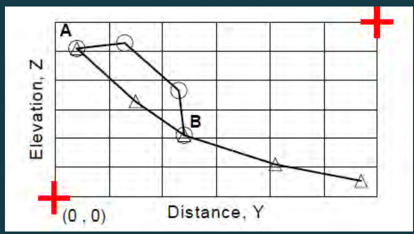
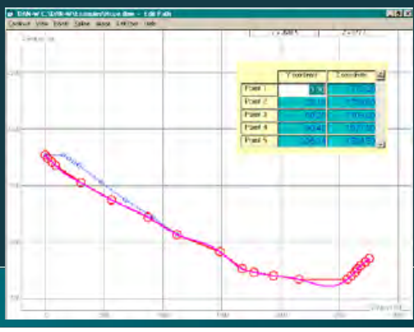
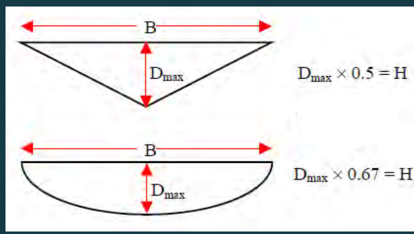
Debris Flow Modelling – Building the Model

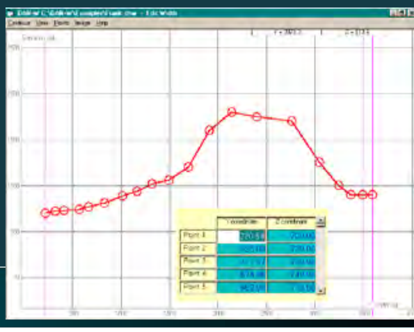
- **Run-out Path Long Section**



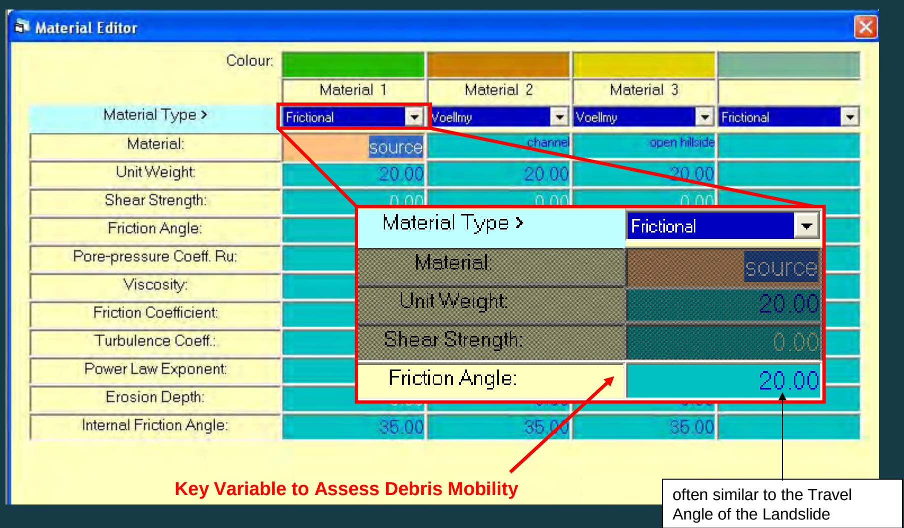


- **Run-out Path Width / Profile**

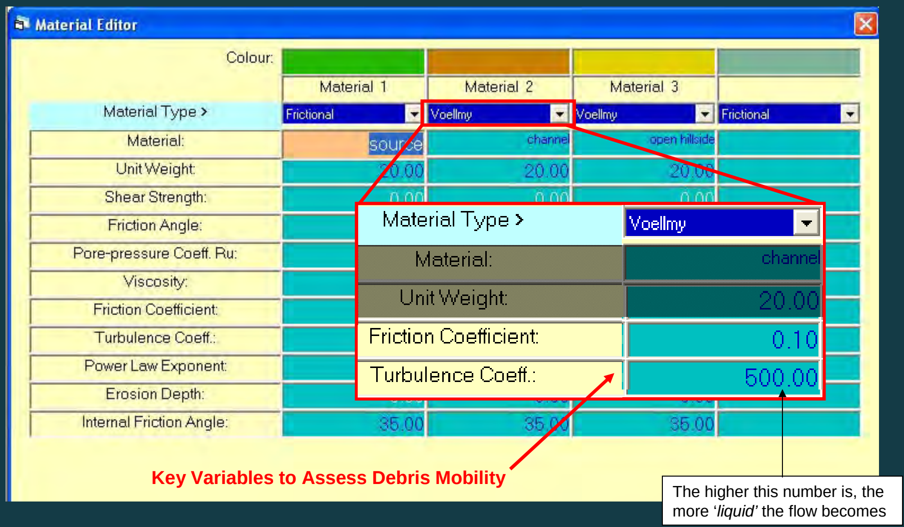




Debris Flow Modelling – Building the Model



Debris Flow Modelling – Building the Model



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Debris Flow Modelling – Running the Model

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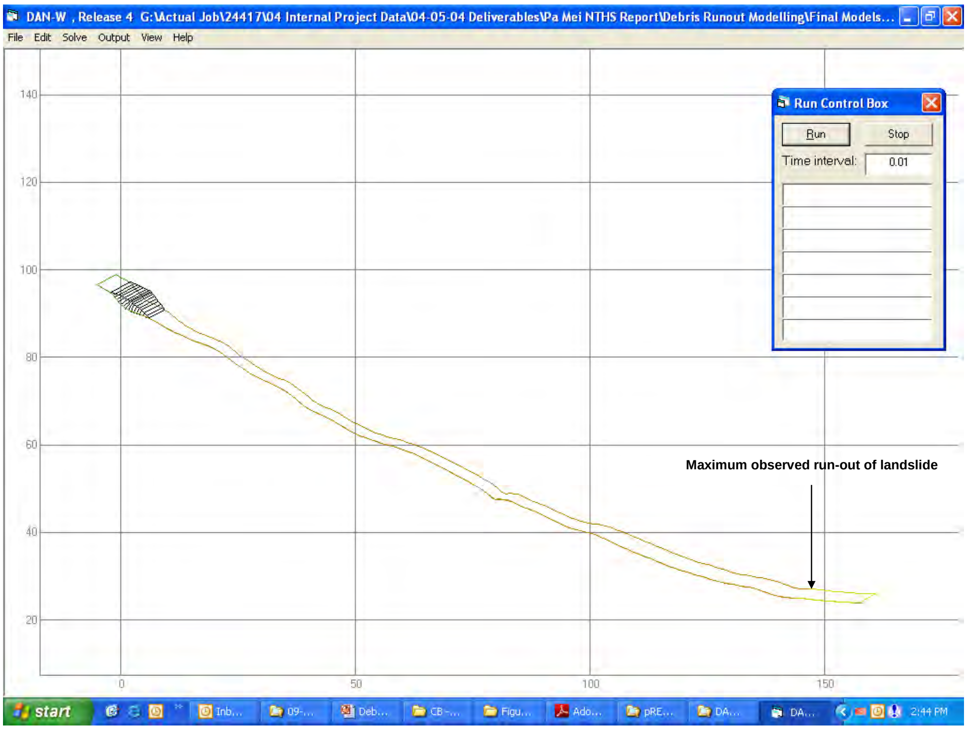
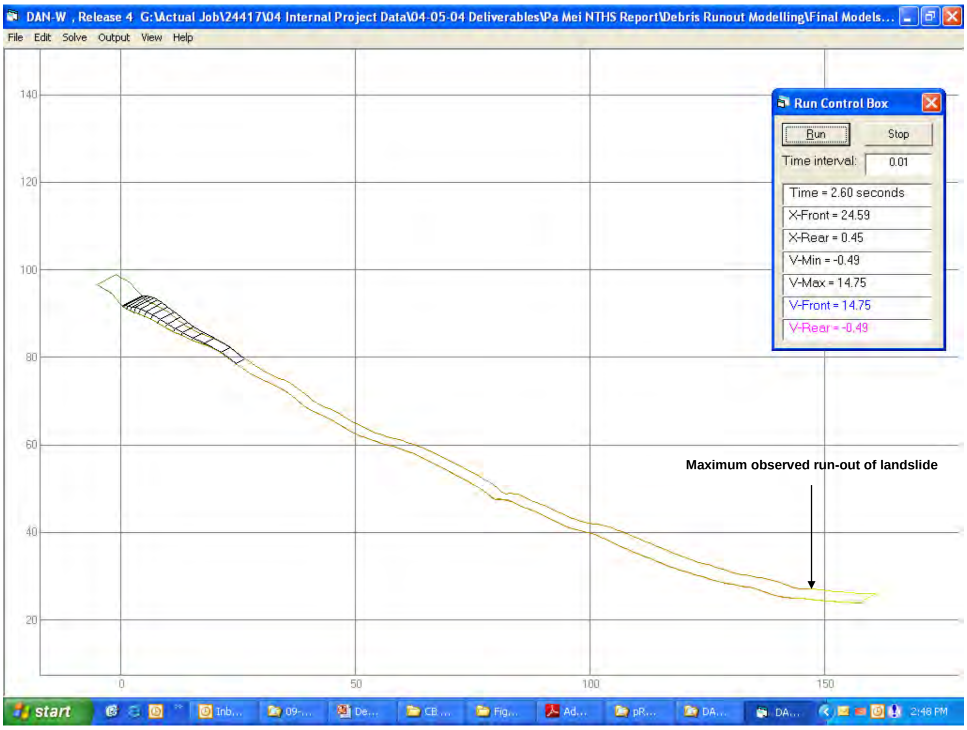

DAN-W , Release 4 G:\Actual Job\24417\04 Internal Project Data\04-05-04 Deliverables\Pa Mei NTHS Report\Debris Runout Modelling\Final Models...
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval:
0.01
140
120
100
80
60
40
20
0
50
100
150
Maximum observed run-out of landslide
start
2:44 PM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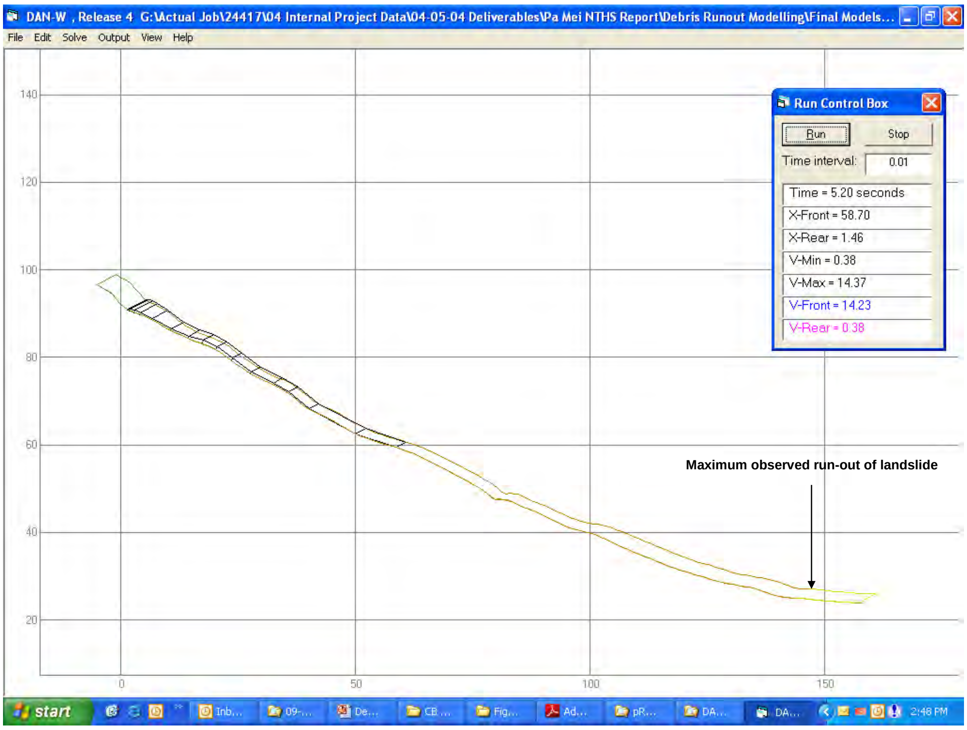
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval:
0.01
Time = 2.60 seconds
X-Front = 24.59
X-Rear = 0.45
V-Min = -0.49
V-Max = 14.75
V-Front = 14.75
V-Rear = -0.49
140
120
100
80
60
40
20
0
50
100
150
Maximum observed run-out of landslide
start
2:48 PM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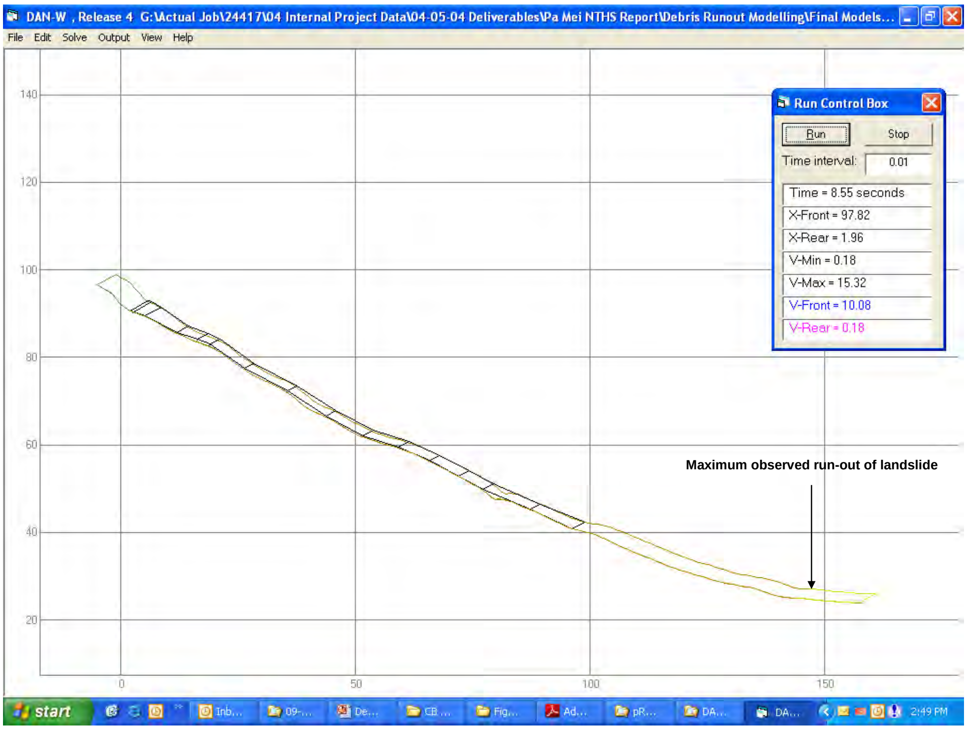
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval: 0.01
Time = 5.20 seconds
X-Front = 58.70
X-Rear = 1.46
V-Min = 0.38
V-Max = 14.37
V-Front = 14.23
V-Rear = 0.38
Maximum observed run-out of landslide
140
120
100
80
60
40
20
0
50
100
150
2:48 PM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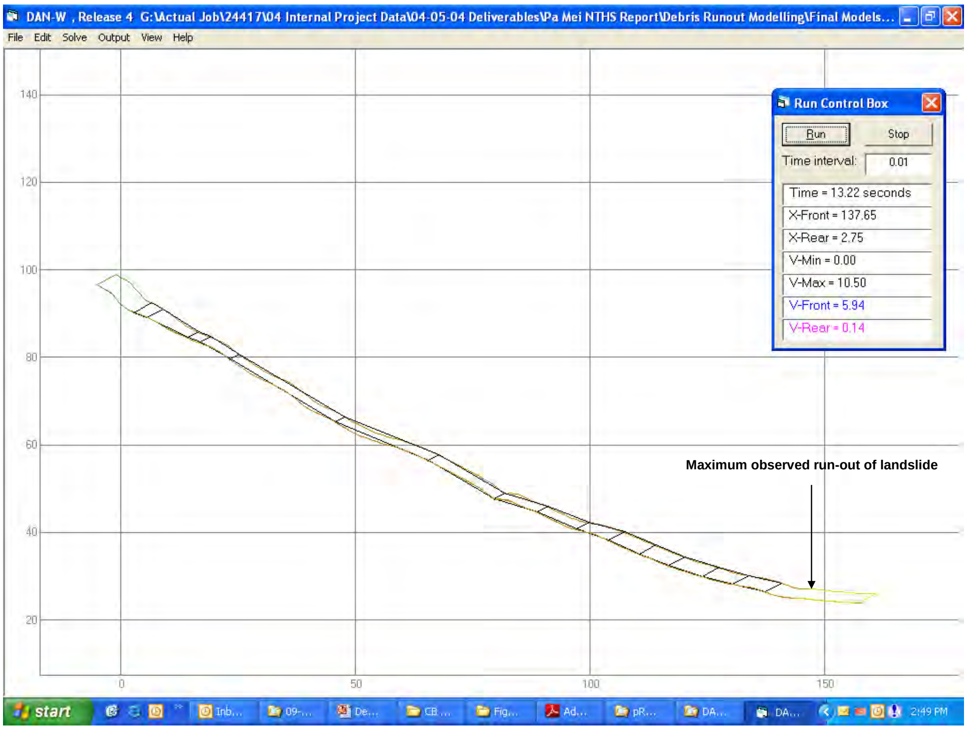
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval: 0.01
Time = 8.55 seconds
X-Front = 97.82
X-Rear = 1.96
V-Min = 0.18
V-Max = 15.32
V-Front = 10.08
V-Rear = 0.18
Maximum observed run-out of landslide
140
120
100
80
60
40
20
0
50
100
150
2:49 PM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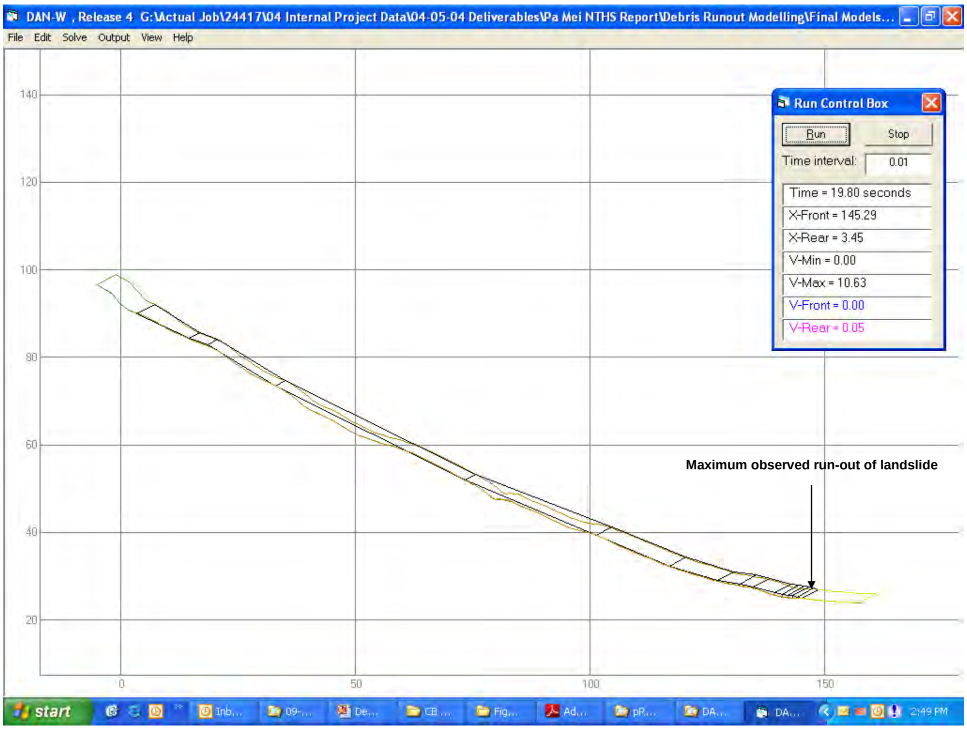
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval: 0.01
Time = 13.22 seconds
X-Front = 137.65
X-Rear = 2.75
V-Min = 0.00
V-Max = 10.50
V-Front = 5.94
V-Rear = 0.14
Maximum observed run-out of landslide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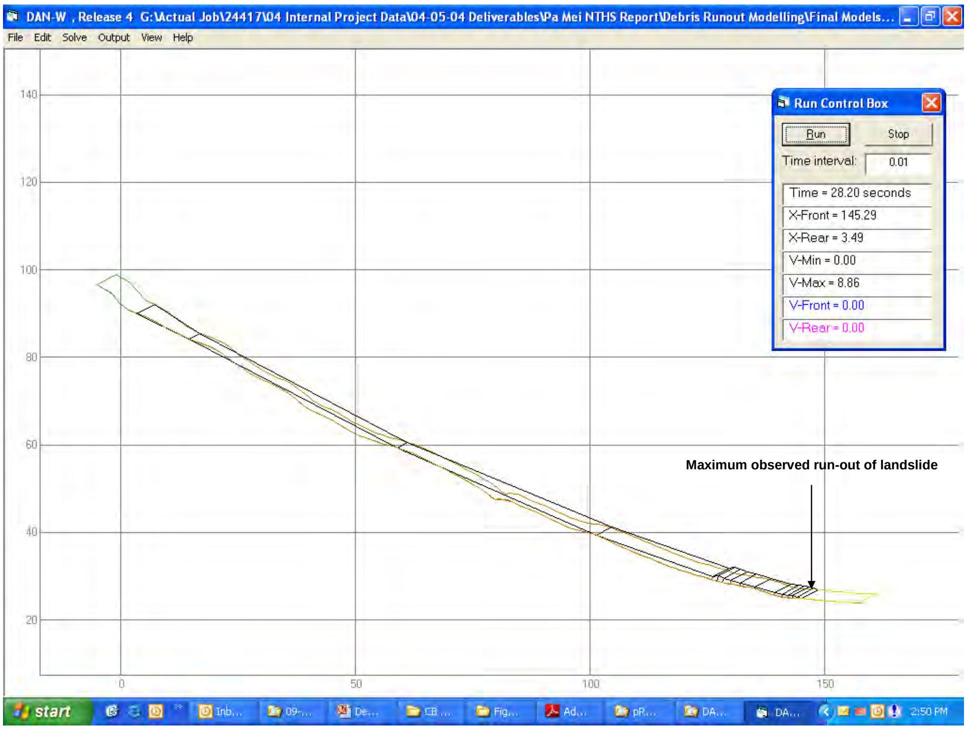
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval: 0.01
Time = 19.80 seconds
X-Front = 145.29
X-Rear = 3.45
V-Min = 0.00
V-Max = 10.63
V-Front = 0.00
V-Rear = 0.05
Maximum observed run-out of landslide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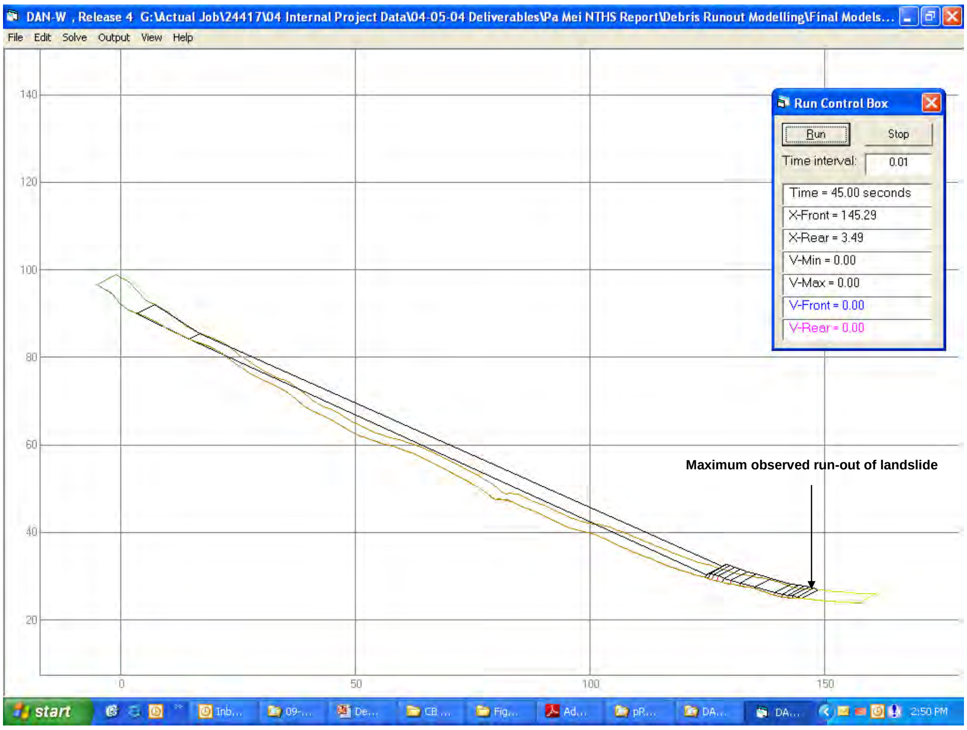
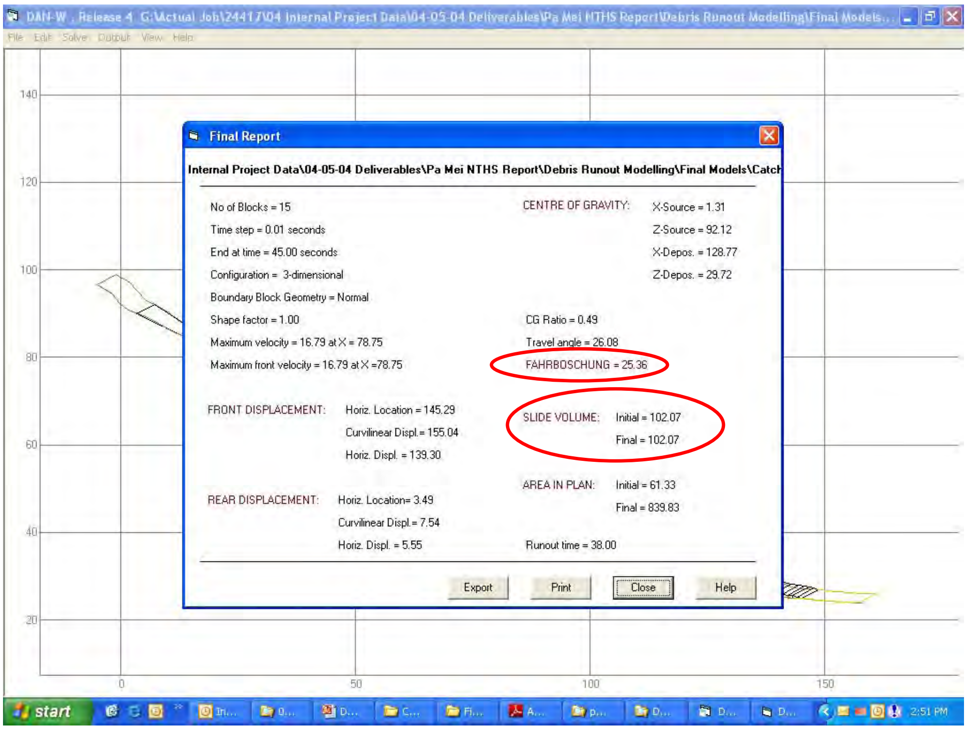
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval: 0.01
Time = 28.20 seconds
X-Front = 145.29
X-Rear = 3.49
V-Min = 0.00
V-Max = 8.86
V-Front = 0.00
V-Rear = 0.00
Maximum observed run-out of landslide
start
2:50 PM


DAN-W , Release 4 G:\Actual Job\24417\04 Internal Project Data\04-05-04 Deliverables\Pa Mei NTHS Report\Debris Runout Modelling\Final Models...
File Edit Solve Output View Help
Run Control Box
Run
Stop
Time interval: 0.01
Time = 45.00 seconds
X-Front = 145.29
X-Rear = 3.49
V-Min = 0.00
V-Max = 0.00
V-Front = 0.00
V-Rear = 0.00
Maximum observed run-out of landslide
start
2:50 PM



Model Checking / Calibration

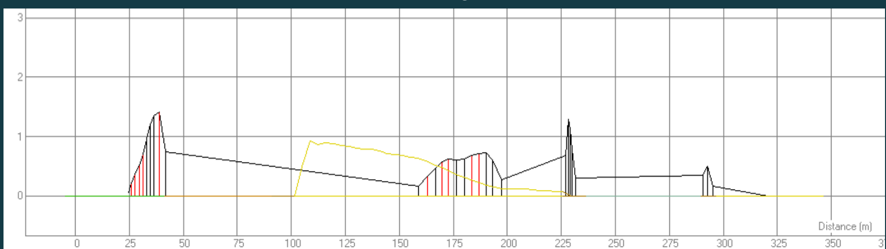
- **Debris distribution**

Volume Estimates from Field Mapping

Chainage (m)	0–13	13–42	42–53	53–91	91–95	95–106	106–145	145–170	170–208	208–224	224–228	228–260	260–282	282–288
Bulked Volume (m^3)	3850#													
Erosion (m^3)		150	25											
Deposition (m^3)		285	170	885	200	455	945	510	215	30	100	110	100*	12
Mass Balance (m^3)		3715	3570	2685	2485	2030	1085	575	360	330	230	120	20	8

* denotes outwash # denotes Bulked volume ≈ source volume x 1.15

Debris Thickness Estimates from Run-out Modelling



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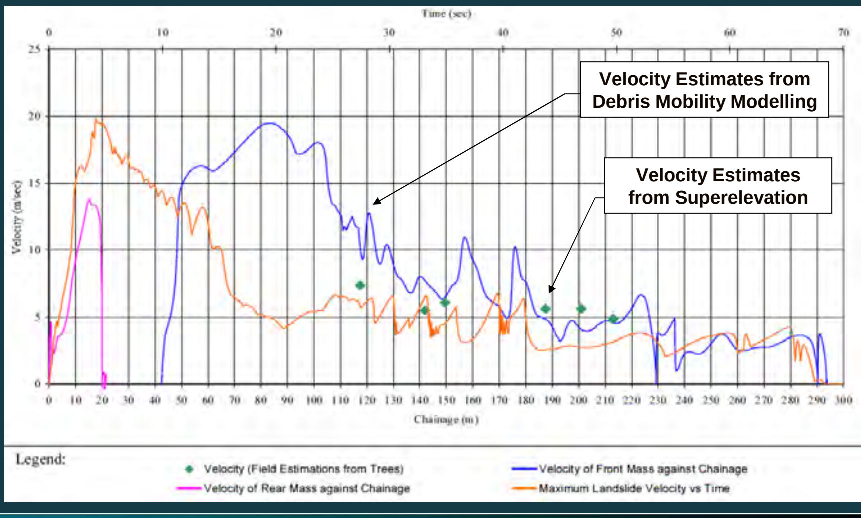
Model Checking / Calibration

- **Landslide velocity**



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Model Checking / Calibration

- **Landslide duration (not often available….)**

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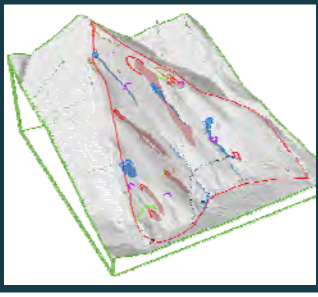
Back Analysis

- Analyse as many '*local*' failures as possible to build a site-specific database of modelling parameters



Landslide No.	Model Type	Landslide Volume	Length of Run-out Trail	Modelled Bulk Friction Angle	Travel Angle
1	Frictional	48.5	44	34.5	32.8
3	Frictional	32.4	49	33	28.7
9	Frictional	130.9	105	32.3	28.9
10	Frictional	404.5	200	29.3	28.3
LS02/08	Frictional	202.9	110	32.7	27.2
LS03/08	Frictional	101.3	95	30.5	28.2
LS04/08	Frictional	98.7	103	28	28.7

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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

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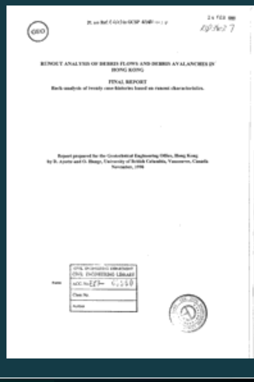
Alternatives to Back Analysis

- **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.

Rheological Model	Model Parameters	
	Open Hillside Failures	Channelised Debris Flows
Friction	$V_D < 400\ m^3$ $\phi_a = 25°$ $V_D \geq 400\ m^3$ $\phi_a = 20°$	$\phi_a = 20°$
Voellmy	-	$\phi_a = 11°$ $\zeta = 500\ m/s^2$


RUNOUT ANALYSIS OF DEBRIS FLOWS AND DEBRIS AVALANCHES IN HONG KONG
FINAL REPORT

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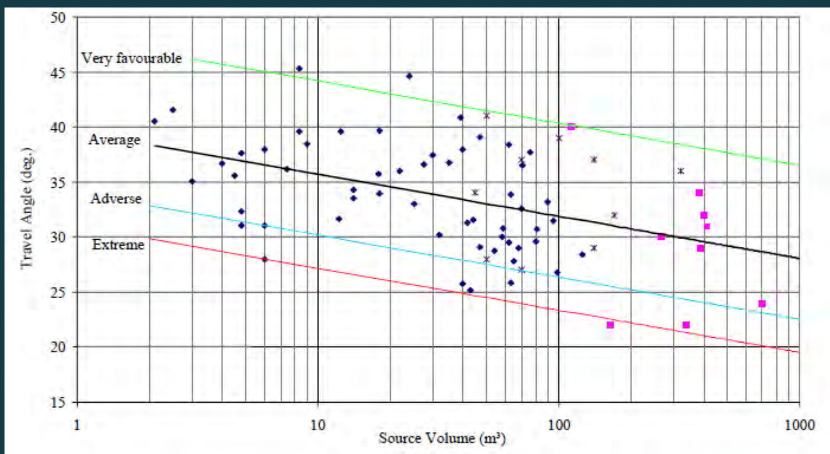
Alternatives to Back Analysis

- **Empirical correlations of Travel Angle and Source Volume (GEO Report 174)**



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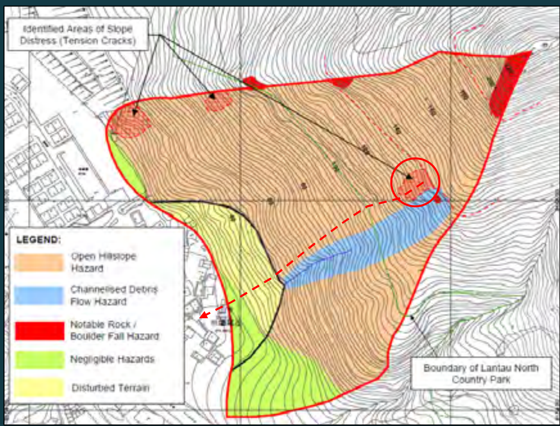
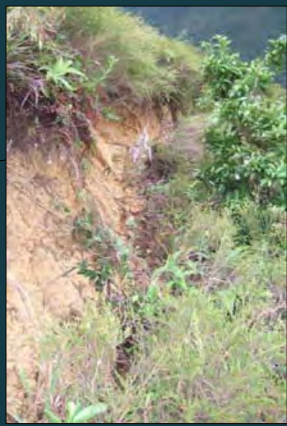
Modelling Potential Landslide Hazards

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





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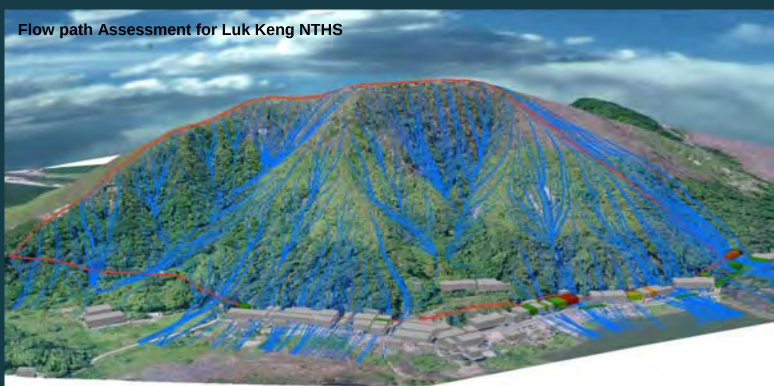
Modelling Potential Landslide Hazards

- **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



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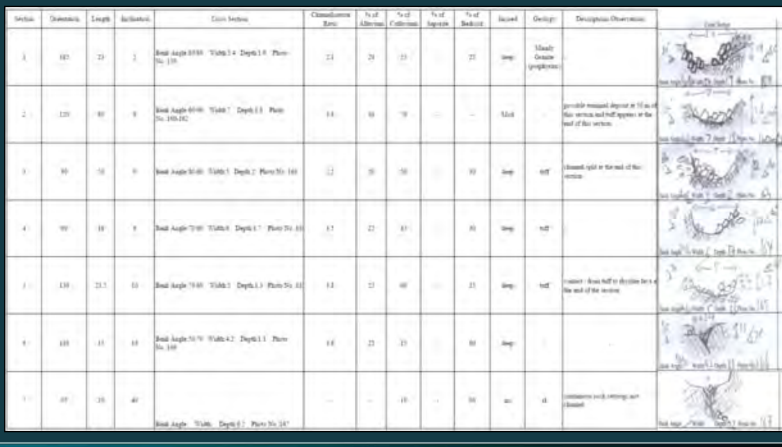
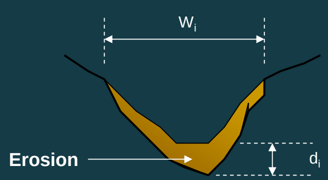
Modelling Potential Landslide Hazards

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



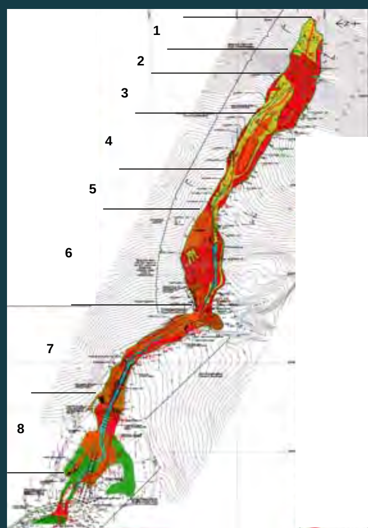
Modelling Potential Landslide Hazards

- **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 ("reaches") of approximately similar character in order to estimate



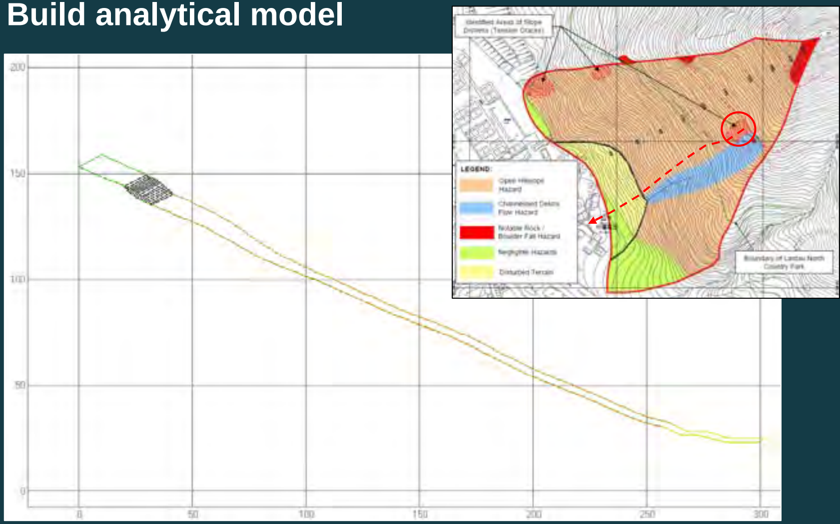
Incremental volume for reach 'i':

$$V_i = Y_i.d_i.W_i$$



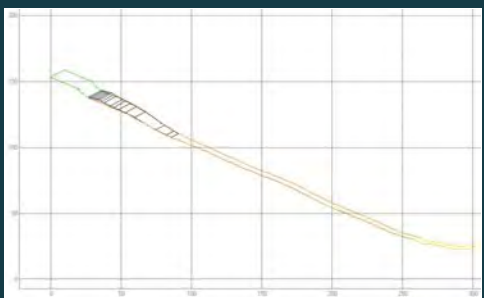
Modelling Potential Landslide Hazards

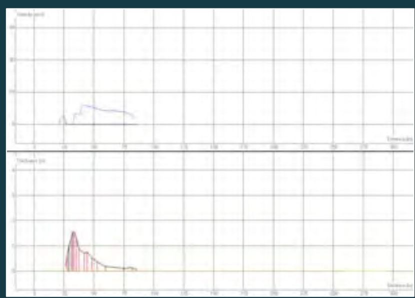
- **Build analytical model**



Modelling Potential Landslide Hazards

- **Conduct Sensitivity Analysis**
  - Upper Bound Case

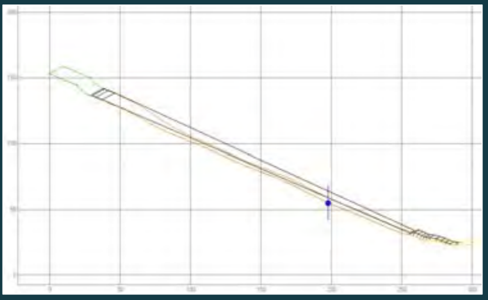


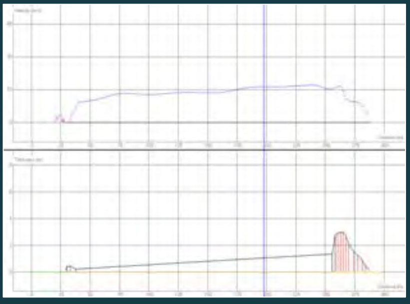


Debris remains confined within hillside area and doesn't affect any down slope facilities

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

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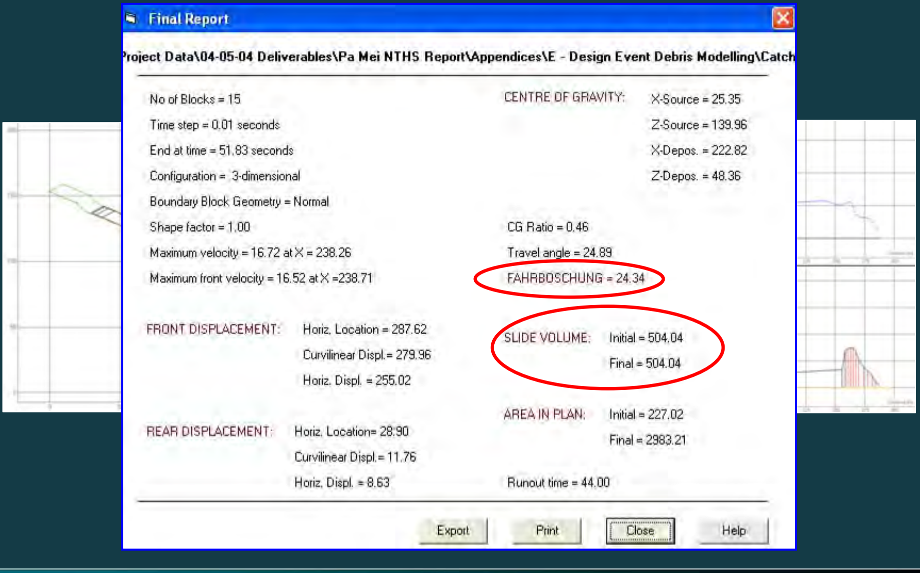
Modelling Potential Landslide Hazards



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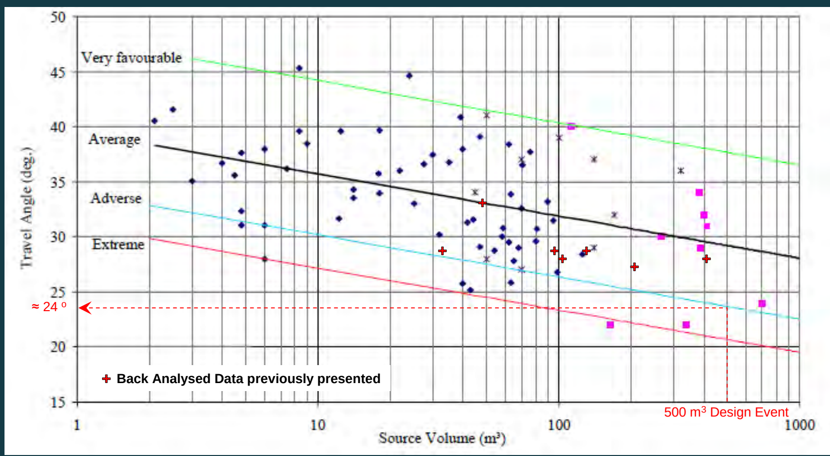
Modelling Potential Landslide Hazards

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



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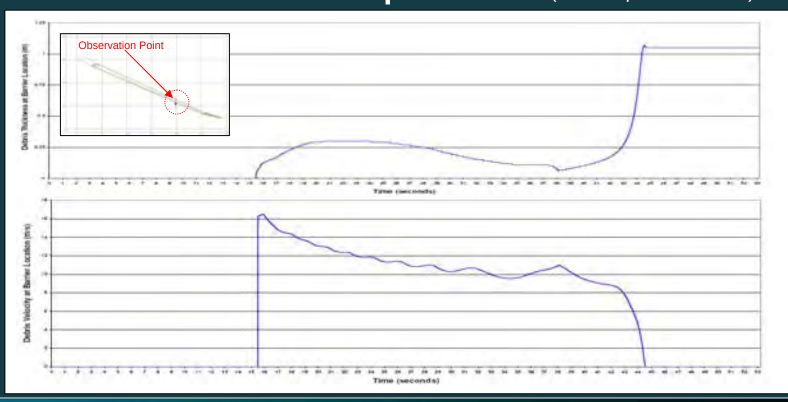
Using the Modelling Data

- **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)*



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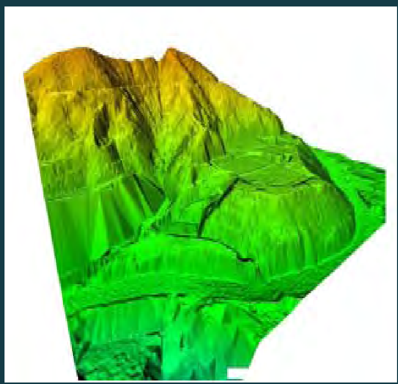
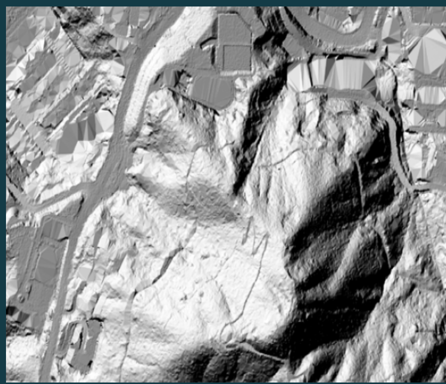
Future Advances

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





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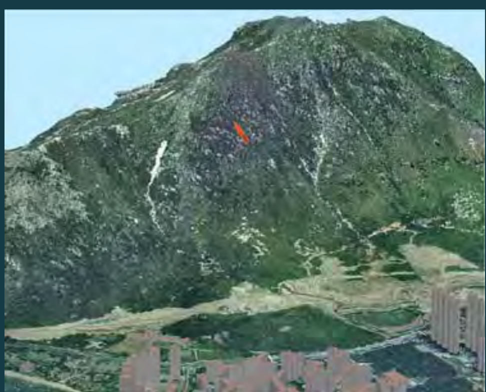
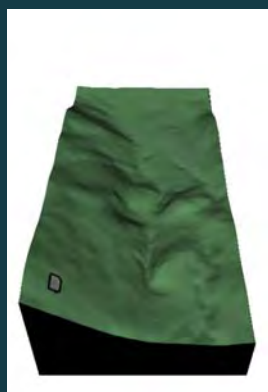
Future Advances

- Development and application of three-dimensional modelling software



GEO 3D-DMM



DAN-3D

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Some Useful References

- GEO Report 104 (2000) Review of Natural Terrain Landslide Debris Resisting Barrier Design + other GEO Reports: http://www.cedd.gov.hk/eng/publications/geo_reports/index.htm
- Hungr (1995) A Model for the Run-out Analysis of Rapid Flow Slides, Debris Flows and Avalanches
- 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

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Thank You

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