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REVIEW OF BENCHMARKING EXERCISE ON LANDSLIDE DEBRIS RUNOUT AND MOBILITY MODELLING

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OVERVIEW

Introduction

Day 3 of the International Forum on Landslide Disaster Management was devoted to presentation and discussion of the Benchmarking Exercise on Landslide Runout Analysis (referred to the Benchmarking Exercise hereafter). The exercise is aimed at assessing whether the emerging field of landslide debris mobility is on its way towards establishing some degree of commonality among different methods used by various parties, taking stock of the progress made and issues to be further addressed, and facilitating interaction among researchers and practitioners.

In this Benchmarking Exercise, participants completed numerical modelling of selected benchmark cases and provided their reports before the Forum. During the Forum, the participants presented key summaries of their findings and took part in discussions on various aspects of dynamic modelling of landslide mobility. The Terms of Reference of the Benchmarking Exercise is included in Appendix A. Professor N R Morgenstern of the University of Alberta, Professor O Hungr of the University of British Columbia and Mr H N Wong of the Geotechnical Engineering Office were on the Review Panel for the Benchmarking Exercise. The Review Panel was supported by a Hong Kong support group, which assisted in extracting, analysing and summarising the benchmarking results. The support team comprised Ms F W Y Ko, Dr J S H Kwan, Dr H W Sun and Mr K C Wong of the Geotechnical Engineering Office.

Twenty-one research groups working on the subject were invited in March 2007 to participate in the Benchmarking Exercise to assemble dynamic numerical models for a total of twelve cases. The cases are placed in three groups, as follows:

- Group A - Verification test cases

  (1) Dam-break scenario
  (2) Laboratory test of dry sand flow prepared by the Swiss Federal Institute of Technology, Lausanne

(3) USGS flume test

- Group B - Debris avalanche/debris flow cases

  (4) Shum Wan Landslide, Hong Kong
  (5) Fei Tsui Road Landslide, Hong Kong
  (6) Sham Tseng San Tsuen Debris Flow, Hong Kong
  (7) 1990 Tsing Shan Debris Flow, Hong Kong

- Group C - Rock avalanche and debris flood cases and a prediction case

  (8) Frank Slide, Canada
  (9) Thurwieser Rock Avalanche, Italy
  (10) 2000 Tsing Shan Debris Flow, Hong Kong
  (11) Tate's Cairn Landslide, Hong Kong
  (12) Lo Wai Debris Flood, Hong Kong

Packages of input materials were distributed to the interested parties in April 2007. By September 2007, a total of 13 teams (from Austria, Canada, France, Netherlands, Hong Kong, Italy, Japan, Norway, Spain and USA) have submitted their modelling results using their respective numerical methods and rheological models. The participating groups were asked to back-analyse the cases using their models, so as to yield the best simulation of observed behaviour. A forward prediction of one potential landslide (Tate's Cairn, Hong Kong) was also included.

This report summarises the submissions made by the various teams on the cases that they have attempted and the methods of analysis, including the rheological models and numerical methods that have been adopted, reviews of the modelling results to diagnose notable common points and discrepancies among them. The report then examines the key issues in relation to application of mobility modelling to landslide risk management and identifies potential areas that warrant further research and development.

Summary of Submissions

Benchmarking Results and Models Adopted
Thirteen groups have submitted their modelling results using their respective numerical methods (Table 1). The cases that have been attempted by the respective groups are listed in Table 2.

The submissions have been summarised in terms of the following key areas of modelling approaches, as detailed in Tables 3(a) to (g):

(a) basic solution approach;
(b) solution dimensions;
(c) solution reference frame;
(d) basal rheology;
(e) internal stress and energy dissipation (other than basal) assumptions;
(f) entrainment of material along flow path; and
(g) variation of basal strength along flow path.

Table 1: List of participants and numerical models used

Team	Model	Denoted as
University of Alberta	Wang	Wang
University of Hong Kong	MADFLOW	MADFLOW
University of Milano Bicocca and FEAT	TOCHNOG	TOCHNOG
Norwegian Geotechnical Institute (NGI)	RAMMS	RAMMS
	DAN3D	DAN3D(NGI)
	FLO-2D	FLO-2D(NGI)
Technical University of Catalonia	FLATMODEL	FLATMODEL
Geotechnical Engineering Office (GEO), Hong Kong	3dDMM	3dDMM
Universite Paris Diderot	SHALTOP-2D	SHALTOP-2D
	RASH3D	RASH3D(Paris)
University of British Columbia (UBC), Vancouver	DAN	DAN
	DAN3D	DAN3D
CEDEX, Madrid	Pastor	Pastor
Vienna University of Technology	PFC	PFC
Kyoto University	Sassa-Wang	Sassa-Wang
Politecnico Di Torino	RASH3D	RASH3D
University at Buffalo, New York	TITAN2D	TITAN2D

Table 2: Cases included in the submissions by participants

Team	Model Denoted As	Group A			Group B				Group C					
		Dam Break	Deflected Sand Flow	USGS Flume test	Shum Wan Landslide	Fei Tsui Road Landslide	1990 Tsing Shan Debris Flow	Sham Tseng San Tsuen Debris Flow	Frank Slide	Thurwieser Rock Avalanche	2000 Tsing Shan Debris Flow	Tate's Cairn Landslide	Tate's Cairn Landslide Forward Prediction	Lo Wai Debris Flood
University of Alberta	Wang	●	●	●	●	●	●	●			●	●		●
University of Hong Kong	MADFLOW		●		●	●				●				
University of Milan	TOCHNOG	●			●				●	●				
NGI, Norway	RAMMS							●						
	DAN3D(NGI)							●				●	●	
	FLO-2D(NGI)											●		
Technical University of Catalonia	FLATMODEL	●		●			●				●	●	●	
GEO, Hong Kong	3dDMM	●	●	●	●	●	●	●	●	●	●	●	●	
Universite Paris Diderot	SHALTOP-2D	●		●	●	●			●					
	RASH3D(Paris)	●												
UBC, Vancouver	DAN	●				●	●		●					
	DAN3D		●		●	●	●	●		●		●	●	
CEDEX, Madrid	Pastor	●	●	●	●	●	●	●	●	●	●	●	●	●
Vienna University of Technology	PFC								●	●				
Kyoto University	Sassa				●	●			●					
Politecnico Di Torino	RASH3D		●			●			●			●	●	
University at Buffalo, New York	TITAN2D		●						●					

Table 3(a): Summary of method of analysis - basic solution approach

Team	Model	Continuum		Discrete
		Differential[(1)]	Integrated[(2)]	Particulate[(3)]
University of Alberta	Wang		x	
University of Hong Kong	MADFLOW		x	
University of Milano Bicocca and FEAT	TOCHNOG	x		
NGI, Norway	RAMMS DAN3D(NGI) FLO-2D(NGI)		x x [(4)] x	
Technical University of Catalonia	FLATMODEL		x	
GEO, Hong Kong	3dDMM		x [(5)]	
Universite Paris Diderot	SHALTOP-2D		x	
	RASH3D(Paris)		x	
UBC, Vancouver	DAN DAN3D		x x [(4)]	
CEDEX, Madrid	Pastor		x [(4)]	
Vienna University of Technology	PFC			x [(6)]
Kyoto University	Sassa-Wang		x	
Politecnico Di Torino	RASH3D		x	
University at Buffalo, New York	TITAN2D		x	

Notes:
(1) Differential solution - equations of motion referenced to an element of mass, with the internal deformation modelled in detail.
(2) Integrated approach - depth-averaged shallow-flow solution, referenced to columns of debris mass above the sliding surface.
(3) Particulate modelling - discrete particle modelling.
(4) Smooth particle hydrodynamic approach is adopted.
(5) Particle-in-cell approach is adopted.
(6) Solution for motion of particles by distinct element method.

Table 3(b): Summary of method of analysis - solution dimensions

Team	Model	2-D(1)	Pseudo-3D(2)	3-D(3)
University of Alberta	Wang	x		
University of Hong Kong	MADFLOW			x
University of Milano Bicocca and FEAT	TOCHNOG	x(4)		x(4)
NGI, Norway	RAMMS			x
	DAN3D(NGI)	x		x
	FLO-2D(NGI)			x
Technical University of Catalonia	FLATMODEL	x		x
GEO, Hong Kong	3dDMM			x
Universite Paris Diderot	SHALTOP-2D			x
	RASH3D(Paris)			x
UBC, Vancouver	DAN		x	
	DAN3D			x
CEDEX, Madrid	Pastor			x
Vienna University of Technology	PFC	x(4)		x(4)
Kyoto University	Sassa-Wang			x
Politecnico Di Torino	RASH3D			x
University at Buffalo, New York	TITAN2D			x

Notes:

(1) Two-dimensional (2-D) - analysing cross-section of a single pre-defined width.

(2) Pseudo-three-dimensional (Pseudo-3D) - analysing cross-sections of varying pre-defined widths along debris trail to account for the plan dimension.

(3) Three-dimensional (3-D) - analysis in plan and in cross-section.

(4) Unlike the other models in the '2-D' or '3-D' category, TOCHNOG and PFC do not involve the use of depth-averaged shallow-flow solution. TOCHNOG and PFC simulate both the failure at the landslide source and the runout of the debris, without the need for imposing a pre-determined failure surface.

Table 3(c): Summary of method of analysis - solution reference frame

Team	Model	Eulerian[1]	Lagrangian[2]	
			With mesh	Mesh Free
University of Alberta	Wang		V	
University of Hong Kong	MADFLOW		N [4]	
University of Milano Bicocca and FEAT	TOCHNOG	•	• [4]	
NGI, Norway	RAMMS	N		
	DAN3D(NGI)			N
	FLO-2D(NGI)	V		
Technical University of Catalonia	FLATMODEL	N		
GEO, Hong Kong	3dDMM	N		
Universite Paris Diderot	SHALTOP-2D	N		
	RASH3D(Paris)	V		
UBC, Vancouver	DAN		N or V	
	DAN3D			N
CEDEX, Madrid	Pastor			N
Vienna University of Technology	PFC			• [5]
Kyoto University	Sassa-Wang	V		
Politecnico Di Torino	RASH3D	V		
University at Buffalo, New York	TITAN2D		V [4]	

Notes:

(1) Eulerian - fixed reference frame.
(2) Lagrangian - moving reference frame.
(3) For models that adopt an integrated approach, their reference column can be:
Normal - depth-averaged in the direction of bed normal; denoted by "N";
Vertical - depth-averaged in the vertical direction; denoted by "V".
(4) Differential approach with adaptive mesh technique.
(5) Distinct element method.

Table 3(d): Summary of method of analysis - basal rheology

Team	Model	Frictional(1)	Voellmy(2)	Three-term(3)	Bingham(4)	Others(5)
University of Alberta	Wang	x (6)				
University of Hong Kong	MADFLOW	x	x		x	
University of Milano Bicocca and FEAT	TOCHNOG	x (7)				
NGI, Norway	RAMMS	x	x			
	DAN3D(NGI)	x	x			
	FLO-2D(NGI)			x		
Technical University of Catalonia	FLATMODEL	x	x			
GEO, Hong Kong	3dDMM	x	x			
Universite Paris Diderot	SHALTOP-2D	x				Pouliquen friction
	RASH3D(Paris)	x	x	x		Pouliquen friction
UBC, Vancouver	DAN	x	x		x	
	DAN3D	x	x			
CEDEX, Madrid	Pastor	x (8)	x (8)		x (8)	Evolution function
Vienna University of Technology	PFC	x (9)				
Kyoto University	Sassa-Wang	x (10)				
Politecnico Di Torino	RASH3D	x	x	x		Pouliquen friction
University at Buffalo, New York	TITAN2D	x				

Notes:

(1) Frictional - shear stress as linear function of total normal stress
(2) Voellmy - frictional term plus a term proportional to the square of velocity
(3) Three-term - frictional, viscous and turbulent
(4) Bingham - constant shear strength plus viscous term
(5) Others - e.g. Pouliquen friction
(6) Consideration of energy changes due to shear distortion of landslide debris is incorporated.
(7) Fully-coupled elastoplastic models for the landslide mass in a differential approach.
(8) Capable to model consolidation of landslide sliding surface.
(9) Rheological model is for inter-particle and particle-wall interaction in a distinct element approach.
(10) Variation of excess pore pressure in sliding surface is modelled.

Table 3(e): Summary of method of analysis - internal Stress and Energy Dissipation (other than basal) assumed in integrated models

Team	Model	Hydrostatic(1)	Rankine(2)	"At Rest" (3)	SH(4)
University of Alberta	Wang		x (5)		
University of Hong Kong	MADFLOW				x
University of Milano Bicocca and FEAT	TOCHNOG	N.A.(6)			
NGI, Norway	RAMMS	x (7)			
	DAN3D(NGI)				x
	FLO-2D(NGI)	x			
Technical University of Catalonia	FLATMODEL	x			
GEO, Hong Kong	3dDMM				x
Universite Paris Diderot	SHALTOP-2D	x			
	RASH3D(Paris)				x
UBC, Vancouver	DAN				x
	DAN3D				x
CEDEX, Madrid	Pastor	x (6)			
Vienna University of Technology	PFC	N.A.(8)			
Kyoto University	Sassa-Wang			x	
Politecnico Di Torino	RASH3D				x
University at Buffalo, New York	TITAN2D				x(9)

Notes:
(1) Zero internal strength (i.e. hydrostatic, k=1).
(2) Rankine stress state.
(3) "At Rest" stress state (i.e. $k_a=k_p$).
(4) Savage-Hutter (SH) model.
(5) Consideration of energy changes due to shear distortion of landslide debris is incorporated.
(6) Fully-coupled elasto-plastic soil models are available for calculation of internal stress distribution.
(7) Based on formulation proposed by Bartelt et al. (1999).
(8) Energy dissipation due to sliding, rolling and bouncing of particles in distinct element method.
(9) Not certain based on information provided.

Table 3(f): Summary of method of analysis - entrainment of material from the path

Team	Model	Not considered	User-specified[(1)]	Algorithm-specified[(2)]
University of Alberta	Wang	x		
University of Hong Kong	MADFLOW		x	
University of Milano Bicocca and FEAT	TOCHNOG			x
NGI, Norway	RAMMS DAN3D(NGI) FLO-2D(NGI)	x x	x	
Technical University of Catalonia	FLATMODEL			x
GEO, Hong Kong	3dDMM		x	
Universite Paris Diderot	SHALTOP-2D	x		
	RASH3D(Paris)	x		
UBC, Vancouver	DAN DAN3D		x x	
CEDEX, Madrid	Pastor		x	
Vienna University of Technology	PFC	x		
Kyoto University	Sassa-Wang	x		
Politecnico Di Torino	RASH3D	x		
University at Buffalo, New York	TITAN2D	x		

Notes:
(1) User-specified - entrainment rate or amount specified by the user.
(2) Algorithm-specified - rate and amount calculated by a pre-scribed algorithm, considering material properties.

Table 3(g): Summary of method of analysis - variation of basal strength along the path

Team	Model	Not Considered	Considered
University of Alberta	Wang	x	
University of Hong Kong	MADFLOW	x	
University of Milano Bicocca and FEAT	TOCHNOG		x
NGI, Norway	RAMMS	x	
	DAN3D(NGI)		x
	FLO-2D(NGI)	x	
Technical University of Catalonia	FLATMODEL	x	
GEO, Hong Kong	3dDMM		x
Universite Paris Diderot	SHALTOP-2D	x	
	RASH3D(Paris)		x
UBC, Vancouver	DAN		x
	DAN3D		x
CEDEX, Madrid	Pastor		x
Vienna University of Technology	PFC	x	
Kyoto University	Sassa-Wang		x
Politecnico Di Torino	RASH3D		x
University at Buffalo, New York	TITAN2D	x	

Related Technical Papers

Apart from providing the modelling results on the benchmarking cases, all of the 13 teams have also submitted technical papers to describe their modelling methodologies and present the results of use of the models. The papers include:

(a) "Analysis of Hong Kong debris flow with an energy based model" *by D Chan, N R Morgenstern, D Tran and X B Wang*
(b) "Landslide mobility analysis using MADflow" *by J H Chen and C F Lee*
(c) "Approach to numerical modelling of long runout landslides" *by G B Crosta, S Imposimato and D Roddeman*
(d) "The 2005 Tate's Cairn debris flow: Back-analysis, forward predictions and a sensitivity analysis" *by J Cepeda*
(e) "Application of 2D-finite volume code FLATModel to landslide runout benchmarking exercises" *by M Hürlimann, V Medina and A Bateman*
(f) "Benchmarking exercise on landslide mobility modelling - runout analyses using 3dDMM" *by J S H Kwan and H W Sun*
(g) "Benchmark exercises for granular flows" *by A Lucas, A Mangeney, F Bouchut, M-O Bristeau and D Mège*
(h) "Two models for analysis of landslide motion: Application to the 2007 Hong Kong benchmarking exercises" *by O Hungr, M McKinnon and S McDougall*
(i) "A SPH depth integrated model with pore pressure coupling for fast landslides and related phenomena" *by M Pastor, T Blanc, M J Pastor, M Sánchez, B Haddad, P*

Mira, J A Fernández Merodo, I Herreros and V Drempetic

(j) "Punta Thurwieser rock avalanche and Frank slide - A comparison based on PFC^{3D} runout models" *by R Poisel, A Preh and O Koc*

(k) "Landslide detachment mechanisms: An overview of their mechanical models" *by R Poisel and A Preh*

(l) "Landslide simulation by geotechnical model adopting a model for variable apparent friction coefficient" *by F W Wang and K Sassa*

(m) "A set of benchmark tests to assess the performance of a continuum mechanics depth-integrated model" *by M Pirulli and C Scavia*

(n) "Benchmarking TITAN2D mass flow model against a sand flow experiment and the 1903 Frank slide" *by S Galas, K Dalbey, D Kumar, A Patra and M Sheridan*

RESULTS OF MODELLING

Group A Cases

The purpose of these cases is to serve as verification exercises. Verification serves to ensure that a given model produces verifiably accurate results for a range of geometries and simple, independently derived, material properties. Verification exercises usually rely on physical laboratory model cases, conducted under closely controlled conditions and with simple materials whose rheological behaviour is well-defined (such as dry sand). Two laboratory test cases and a dam-break scenario are included in this group for benchmarking the modelling results. Seven teams have attempted the dam-break scenario and the laboratory test of Deflected Sand Flow, while five teams attempted the USGS Flume Test.

Dam-break Scenario

This is a 2-D case with an analytical solution available for direct comparison with the simulation results and validating the debris runout and debris profile simulated by the numerical models at different times after the 'dam-break'. In the analytical solution, the debris mass is assumed to be frictionless internally and resistance to flow is derived from basal friction only. Seven teams submitted simulation results for this case (see Table 4).

Table 4: Teams participating in modelling of the dam break scenario

Team	Model	Remarks
University of Alberta	Wang	The initial boundary condition adopted is different from the analytical solution; the assumption of energy loss due to internal shear distortion calculated by the model is not considered by the analytical solution
University of Milano Bicocca and FEAT	TOCHNOG	The model considers frictional material when calculating the internal stress, i.e. different from the frictionless material assumed by the analytical solution
Technical University of Catalonia	FLATMODEL*	Results submitted before the Forum were clarified and replacement figures were provided after the Forum. Observation presented is based on the resubmitted results
GEO, Hong Kong	3dDMM *	A special 2-D version is used
Universite Paris Diderot	SHALTOP-2D *	
	RASH3D *	RASH3D was used for comparison purposes
UBC, Vancouver	DAN3D *	A special 2-D version is used
CEDEX, Madrid	Pastor *	A special 2-D version is used, “wet bed” simulation results are provided

Figure 1 depicts the simulation results produced by various models of the participants at 10 s, 20 s and 30 s after ‘dam break’.

<u>Observations</u>

(a) With the same basal rheology and material parameters specified in the exercise, the six models marked * in Table 4 above, viz. FLATMODEL, 3dDMM, SHALTOP-2D, RASH3D, DAN and Pastor, give simulation results that match well with the analytical solutions at 10 seconds, 20 seconds and 30 seconds.

Notes:

- SHALTOP-2D and FLATMODEL gives an excellent match at all points.
- At the distal end of the debris where the debris depth is within about 1 m, the 2-D version of DAN3D gives a simulated debris depth that is greater than the analytical solution.
- The 2-D version of 3dDMM tends to give a simulated debris depth that is slightly smaller than the analytical solution.
- The “wet bed” simulation results of Pastor match well with the analytical solution; the depth of “wet bed” is 1 m.
- The RASH3D results provided by the participant show some minor deviations from the analytical solution. It is not certain whether this is related to the grid/mesh size adopted in the modelling.

(b) A landslide mass with internal friction was adopted in TOCHNOG’s and Wang’s modelling. The modelling results are not comparable to the analytical solution, which assumes that the debris mass has no internal friction.

(c) The source conditions and initial boundary conditions adopted in Wang's modelling were different from the analytical solution. Direct comparison between the modelling results and the analytical solutions is not viable.

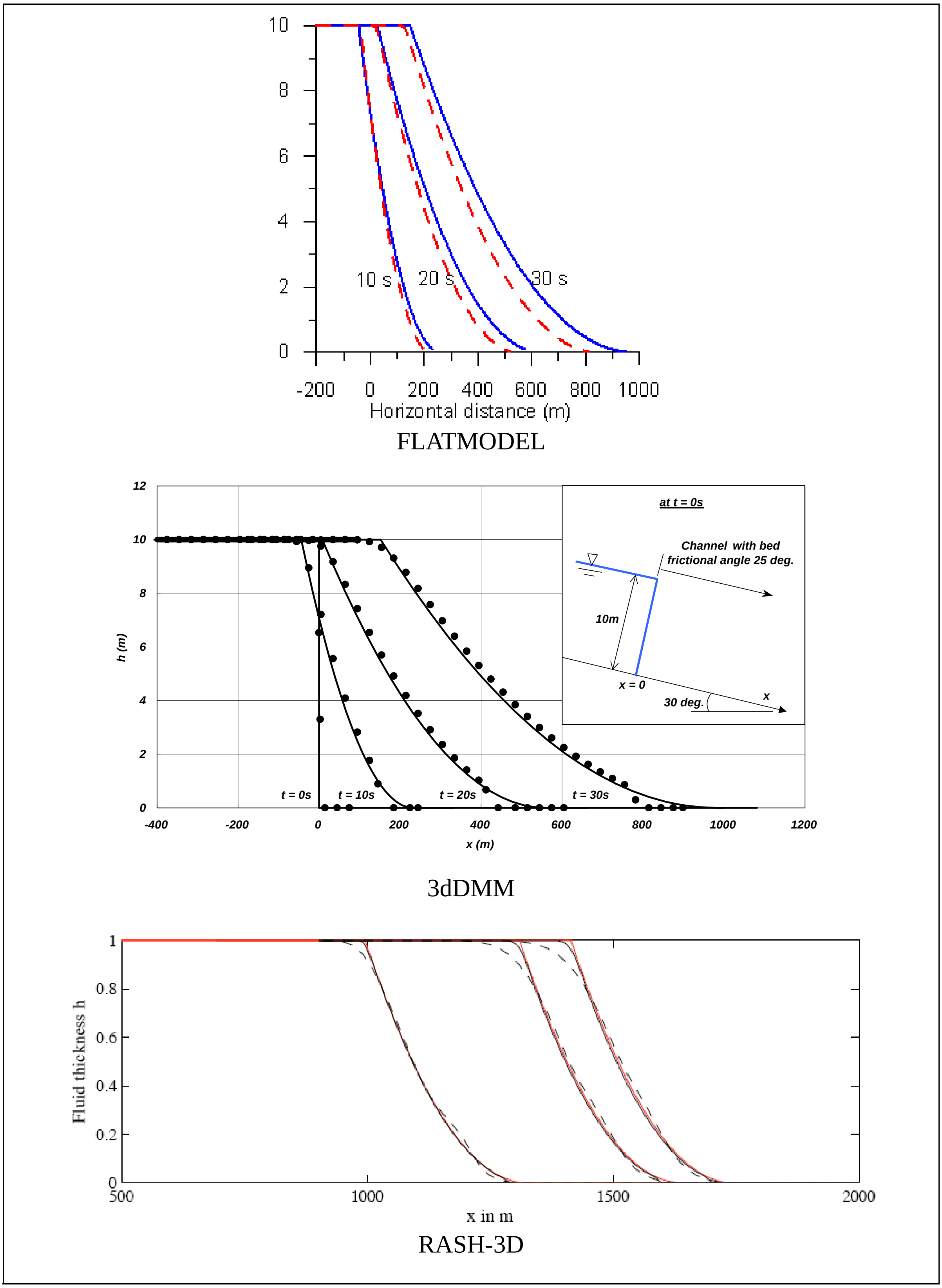
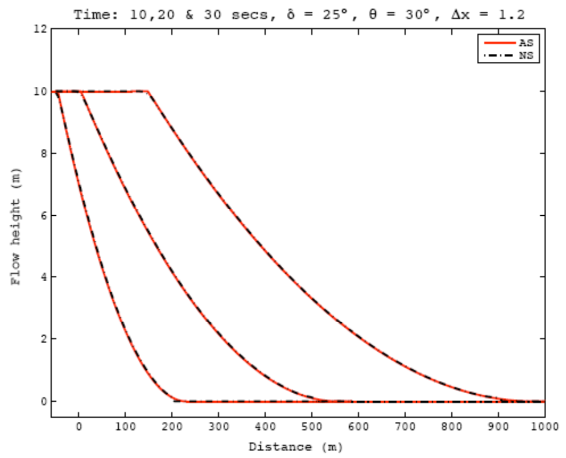
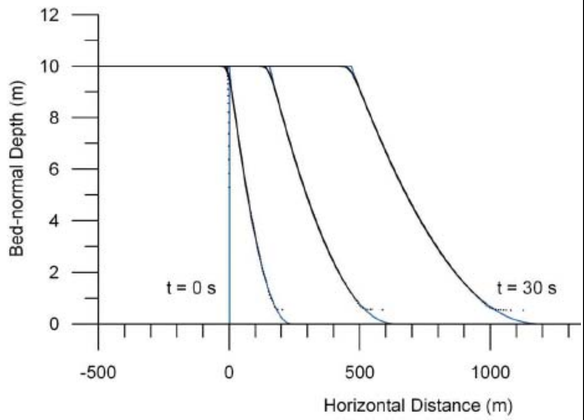


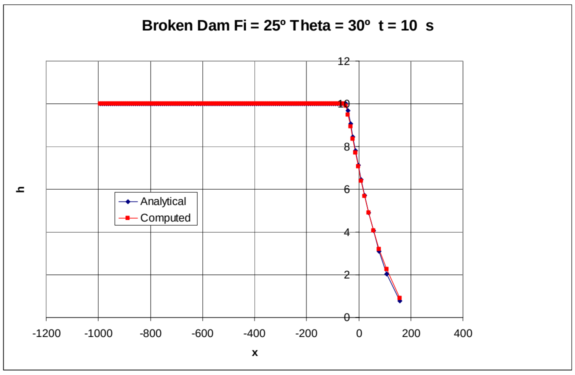
Figure 1: Simulation results by various models for the dam break scenario



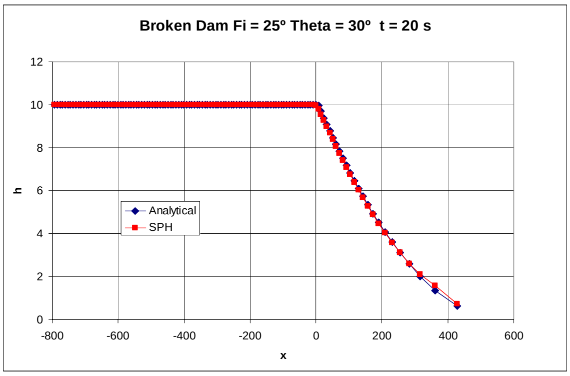
SHALTOP –2D



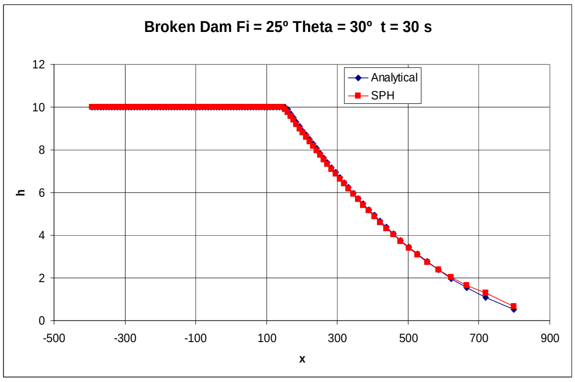
DAN3D



Pastor (at 10s)



Pastor (at 20s)



Pastor (at 30s)

Figure 1 (Con't): Simulation results by various models for the dam break scenario

Deflected Sand Flow

The deflected sand flow experiment was carried out by the Rock Mechanics Laboratory of the Swiss Federal Institute of Technology in Lausanne (EPFL). The experiment involves releasing dry fine sands from a box placed in a flume, which was set up using two inclined planes sloping at different angles. Seven teams submitted simulation results for this case (see Table 5).

Table 5: Teams participating in modelling of the deflected sand flow

Team	Model	Remarks
University of Alberta	Wang	2D model
University of Hong Kong	MADFLOW *	
GEO, Hong Kong	3dDMM *	
UBC, Vancouver	DAN3D *	
CEDEX, Madrid	Pastor *	
Politecnico Di Torino	RASH3D *	A different bed friction (35^o) is adopted
University at Buffalo, New York	TITAN2D *	

Figure 2 depicts the simulation results produced by the various models of the participants. The contour lines at deposition zones of the test results, together with simulation results corresponding to thickness of 0.03 m and 0.005 m respectively, are marked for easy comparison.

<u>Observations</u>

(a) Based on the use of relevant basal rheology and material parameters, all the six 3-D models marked * in Table 5 produce simulations that resemble the test in respect to the overall reach of the sand flow and the broad shape of sand deposition.

(b) At 0.03 m debris depth, MADFLOW, 3dDMM and DAN3D give a consistent maximum runout, which matches well with the test results. The maximum runout at 0.03 m debris depth given by Pastor and RASH3D is slightly less than that of the test results, while the maximum runout of TITAN2D is greater than that of the test results. In respect of the area bounded by the 0.03 m contour, the test results match better with the simulation results of MADFLOW, 3dDMM and DAN3D, than with the simulation results of Pastor, RASH3D and TITAN2D.

(c) At 0.005 m debris depth, MADFLOW produces the best match with the test results. While the results of DAN3D match well with the test results at the debris front, some debris is seen to be deposited along the trail which is not observed in the test. Pastor, 3dDMM and RASH3D give reasonable simulation results but they slightly over-estimate the extent of the sand deposition.

(d) It should be noted that a better match with the test results does not necessarily mean better performance of the model, given the possible variations in material properties and test conditions. However, judging from (b) and (c) above, it appears that MADFLOW, 3dDMM, DAN3D, RASH3D and Pastor produce overall trend results that are consistent with the test results. TITAN2D results in a much greater degree of spreading of the debris deposition, as compared with the results from the other models and from the test results. This can also be illustrated by a comparison of the maximum debris deposition depth as obtained by the various models, as summarised in Table 6.

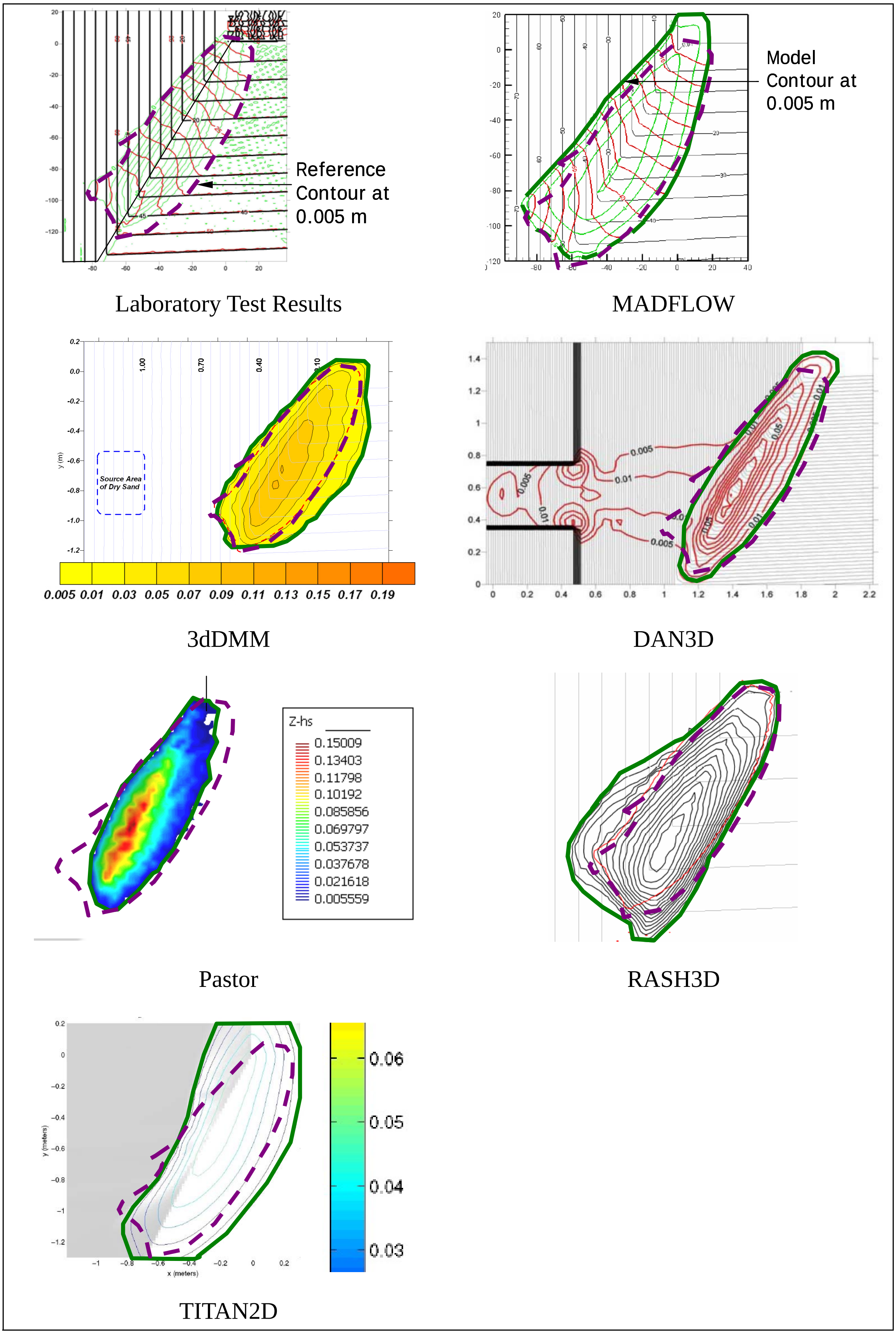


Figure 2: Simulation results by various models for the deflected sand flow experiment

Table 6: Maximum debris depth estimated by various models

Team	Model	Maximum Debris Depth (m)
University of Hong Kong	MADFLOW *	0.110 – 0.120
GEO, Hong Kong	3dDMM *	0.090 – 0.100
UBC, Vancouver	DAN3D *	0.080 – 0.090
CEDEX, Madrid	Pastor *	0.130 – 0.150
Politecnico Di Torino	RASH3D *	0.075
University at Buffalo, New York	TITAN2D	0.040 – 0.050
Notes: The maximum debris depth measured in the test is 0.13 m.		

(e) The variations in the maximum debris deposition depth and in the spatial extent and profile of the debris deposition zone among the simulation results, including those obtained by the models marked * in Table 6, are notable. This may be related to the different assumptions made of the internal stress and the different numerical approaches (e.g. SPH and PIC) adopted in the models. While the runout distance is usually less sensitive to these factors, they may affect the debris deposition profile and its spatial coverage in some circumstances.

USGS Flume Test

The USGS reported two dry sand flow experiments using a miniature flume (Iverson and Delinger, 2004). The two experiments, Experiments A and B, were conducted with flume bed of different topography. Five teams attempted this benchmarking case, four of which used 3-D numerical models for the simulation (see Table 7). Two of the four teams submitted simulation results for both Experiments A and B.

Table 7: List of teams participating in modelling the USGS flume test

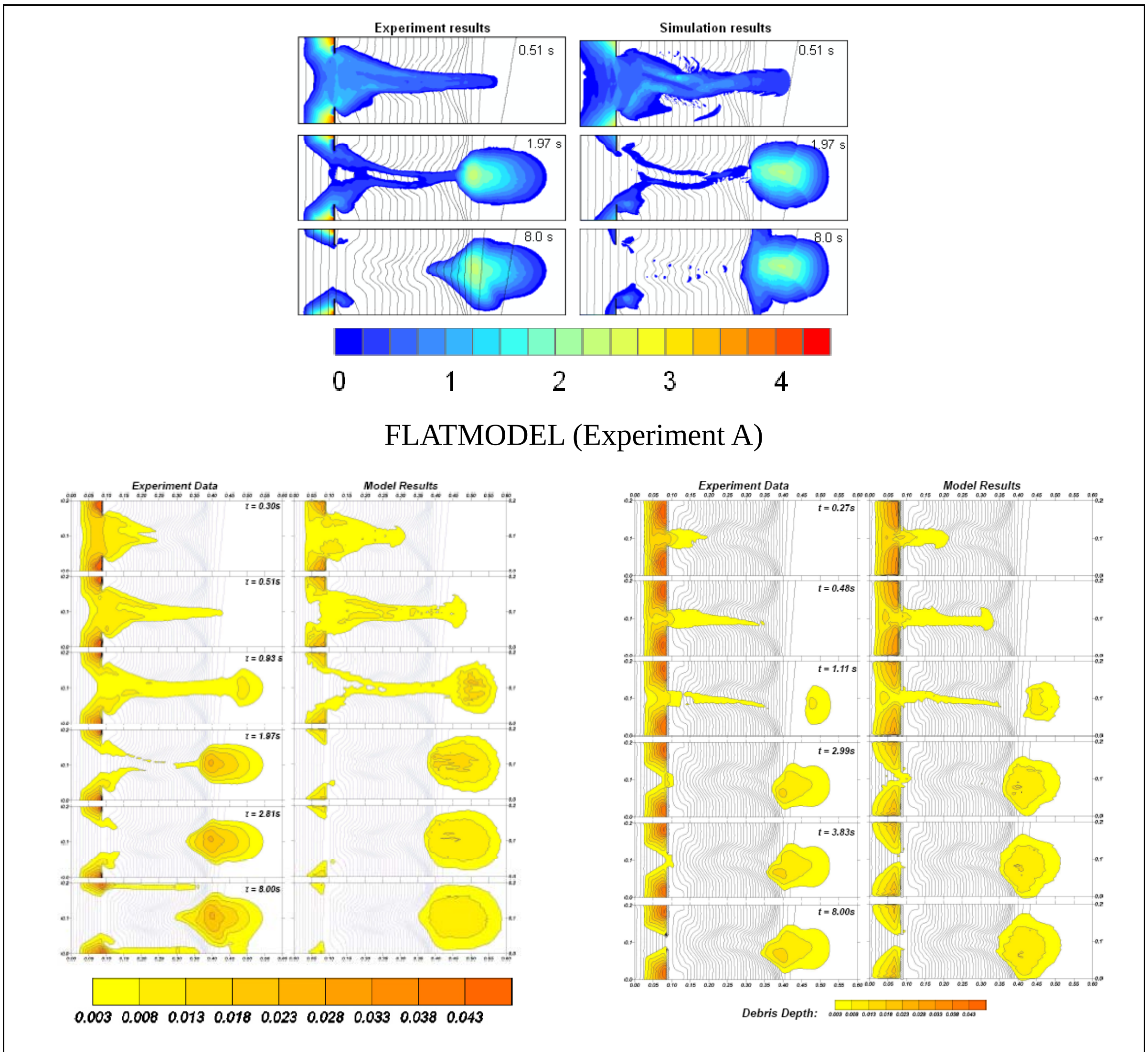
Team	Model	Remark
University of Alberta	Wang	2D model
Technical University of Catalonia	FLATMODEL *	Experiment A only
GEO, Hong Kong	3dDMM *	Both Exp. A and B attempted
Universite Paris Diderot	SHALTOP-2D *	Experiment A only
CEDEX, Madrid	Pastor *	Both Exp. A and B attempted

Figure 3 depicts the simulation results produced by the various models.

Observations

(a) Based on the use of relevant basal rheology and material parameters, all the four 3-D models marked * in Table 7 above give simulation results that resemble the experimental results in respect of debris profiles and the overall runout of the debris.

(b) The experimental results provide good information on the runout and deposition of the debris, as well as the profile of the material that remains at the source, corresponding to different simulation times (up to 8 seconds). The four 3-D models also provide clear information on these aspects, which facilitates a direct comparison. The simulation results of the FLATMODEL, 3dDMM and SHALTOP-D are very similar, and they generally match well with the experimental results in respect of the debris runout. These models are able to capture the overall behaviour of the sand flows and the results reflect the influence of the 3-D profiles of the test flumes. Pastor also appears to give simulation results that are similar to the experiment, but judging from the contour plots given by the participant, the resolution of the result is notably coarser than those given by FLATMODEL, 3dDMM and SHALTOP-2D. It is not certain whether this might have been affected by the DEM/boundary conditions adopted in Pastor's modelling for this case.



FLATMODEL (Experiment A)

3dDMM (Experiment A)

3dDMM (Experiment B)

Figure 3: Simulation results by various models for the USGS flume test

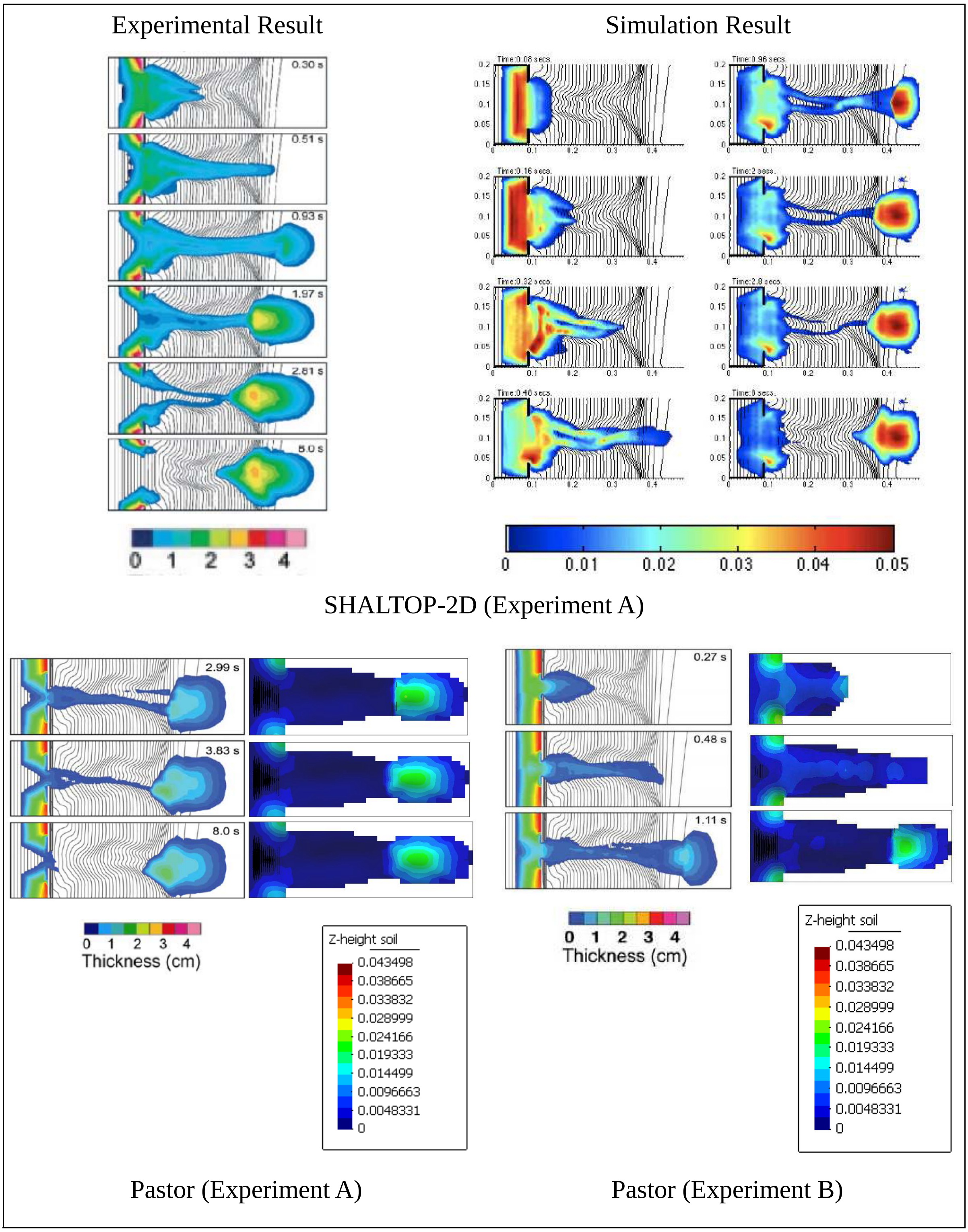


Figure 3 (Con't): Simulation results by various models for the USGS flume test

(c) As observed in the simulation of the deflected sand flow, there are some variations in the extent and profile of the deposition zone produced by the 3-D models. This can be illustrated by a comparison of the maximum debris depth when time is at 8 seconds, as summarised in Table 8 below. 3dDMM under-estimates the deposition depth, as its results show a more dispersed deposition zone, with larger lateral spreading as compared with the others.

(d) All four 3-D models over-estimate the amount of material detached from the source, i.e. less material remains in place at the source as compared with the experimental results. This is anticipated because these dynamic models do not model the geometry of the slope at limiting equilibrium condition at the source. SHALTOP-2D gives simulation results that differ noticeably from the experimental results at and near the source, showing sand deposition around the opening of the sand discharge. It is not clear whether this might have been affected by the assumptions adopted by SHALTOP-2D in simulating the conditions at and near the source area.

Table 8: Maximum simulated debris depth at 8 seconds

Team	Model	Maximum Debris Depth (m)	
		Exp. A[1]	Exp. B[1]
Technical University of Catalonia	FLATMODEL	0.026 – 0.028	Not submitted
GEO, Hong Kong	3dDMM	0.008 – 0.013	0.008 – 0.013
Universite Paris Diderot	SHALTOP-2D	~0.05	Not submitted
CEDEX, Madrid	Pastor	0.023 [2]	0.020 [3]

Notes:
(1) The maximum debris depth measured in Experiment A and Experiment B at t = 8 seconds are 0.023 m and 0.016 m respectively.
(2) Simulation result at t = 3.99 seconds; results at t = 8 seconds were not submitted.
(3) Simulation result at t = 1.11 seconds; results at t = 8 seconds were not submitted.

Group B and C Cases

A review of the simulation results of the calibration cases in Group A indicates that certain models perform consistently and produce similar modelling results when in direct comparison with each other, although some variations exist among their debris deposition depths and lateral spreading of the debris. The results of some other models appear to be less consistent, possibly because of the limitations of their formulations in performing 3-D modelling, particularly for complex 3-D ground profiles and the difficulty in realistically accounting for a wide range of material properties and landslide types.

The outcome of the modelling of the nine actual landslide cases in Groups B and C are summarised below.

Tate's Cairn Landslide

Seven teams set up their dynamic models for simulation of the Tate's Cairn landslide as summarised in Table 9. Five of the seven teams used Voellmy rheology in the simulations. FLATMODEL also considers turbulence in its simulations, but it calculates the turbulent friction based on the Chezy coefficient. (The square of the Chezy coefficient is equivalent to the Voellmy turbulence coefficient). Apart from assuming the Voellmy rheology, NGI also carried out a series of back-analyses using FLO-2D based on quadratic rheology. The UBC group presented sets of results in the form of a simple parametric study.

Table 9: Team participating in simulation of Tate's Cairn landslide and parameters adopted

Team	Model	Base Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Alberta	Wang	25	-
NGI, Norway	DAN3D(NGI) *	15	1000
	FLO-2D	#	#
Technical University of Catalonia	FLATMODEL	23	400 (2)
		25	998.6 (2)
GEO, Hong Kong	3dDMM *	15	500
UBC, Vancouver	DAN3D *	5.7 (f = 0.1) (1)	300
		16.7 (f = 0.3)	
		26.6 (f = 0.5)	
		5.7 (f = 0.1) (1)	500
		16.7 (f = 0.3)	
		26.6 (f = 0.5) (1)	
CEDEX, Madrid	Pastor *	16.7 (f = 0.3)	500
Politecnico Di Torino	RASH3D	25	1000

Notes:

(1) The sets of input parameters, i.e. (f = 0.1, ξ = 300 m/s^2), (f = 0.1, ξ = 500 m/s^2) and (f = 0.5, ξ = 500 m/s^2), do not produce good simulation results in terms of debris reach as compared with field observations and therefore they are not taken into consideration in the result comparison.

(2) Calculated based on the reported Chezy coefficient.

\# The team back-analysed the case using quadratic rheology. A series of back-analyses was preformed, the set of parameters that produce the best-fit results are in the range of yield strength of 9 to 10 Pa, viscosity of 3 to 11 Pa·s and Manning's n-value of 0.04.

Figure 4 shows the debris flow paths and the debris runouts. All the simulations produce a good match with the observed runout distance. The simulated debris travelling times and maximum debris deposition depths are given in Table 10.

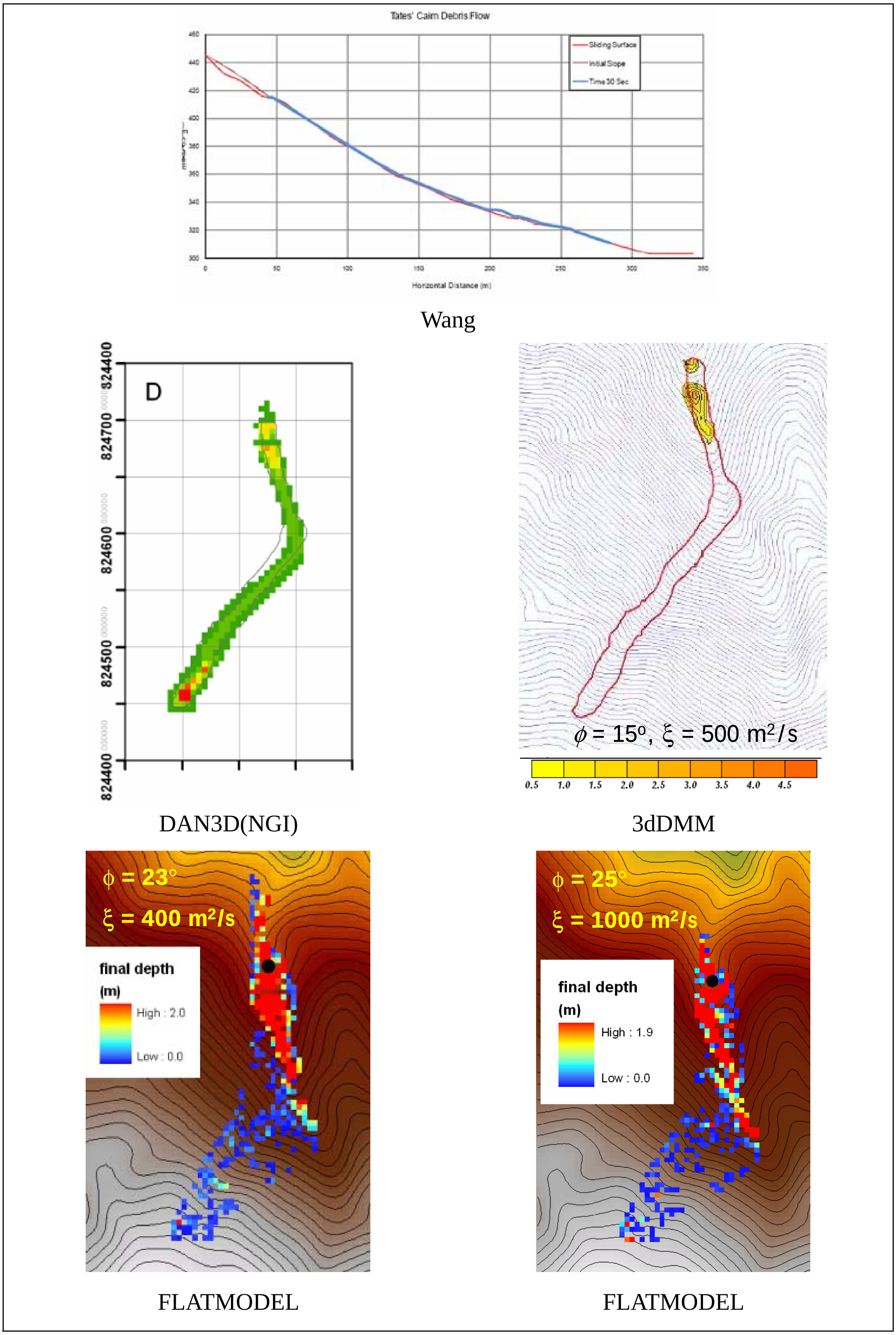


Figure 4: Simulation results by various models for Tate's Cairn landslide

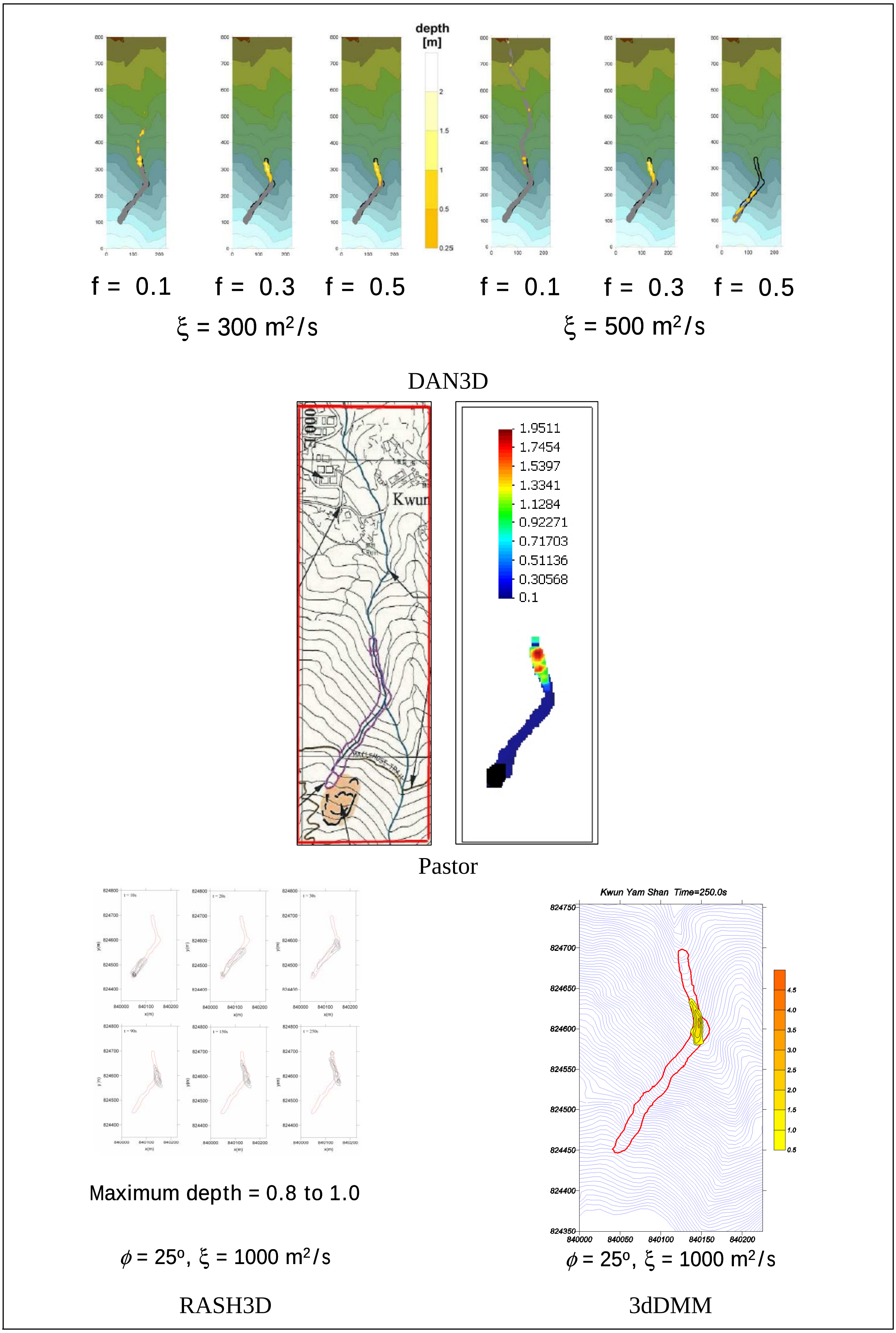


Figure 4 (Con't): Simulation results by various models for Tate's Cairn landslide

Table 10: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Base Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)	Debris Travelling Time (s)	Maximum Debris Depth (m)
University of Alberta	Wang	25	-	30	-
NGI, Norway	DAN3D(NGI)*	15	1000	90	2.5 – 3.0
	FLO-2D	N.A.	N.A.	-	-
Technical University of Catalonia	FLATMODEL	23	400	-	1.5 – 2.0
		25	1000	-	1.5 – 2.0
GEO, Hong Kong	3dDMM *	15	500	40	2.5 – 3.0
UBC, Vancouver	DAN3D *	16.7 (f = 0.3)	300	-	1.0 – 1.5
		26.6 (f = 0.5)		-	1.0 – 1.5
		16.7 (f = 0.3)	500	-	1.0 – 1.5
CEDEX, Madrid	Pastor *	16.7 (f = 0.3)	500	51	1.5 – 2.0
Politecnico Di Torino	RASH3D	25	1000	250	0.8 – 1.0

Observations

(a) A direct comparison of the overall reach of the debris and debris flow path among the four models marked * in Table 6 above, i.e. DAN3D(NGI), 3dDMM, DAN3D and Pastor, is possible as they use similar basal rheology and material parameters. The four models give comparable simulation results.

(b) There are some variations in the maximum debris deposition depth, as well as the extent and profile of the debris deposition zone among the simulation results, including those obtained by the 3D models marked *.

(c) Debris travelling time has not been reported by all teams, but for those that have reported, viz. 3dDMM and Pastor, their debris travelling times are reasonably close to each other.

(d) Although FLATMODEL and RASH3D have adopted almost the same set of material parameters, they give different simulation results. The extent of debris trail simulated by the FLATMODEL appears to be larger as compared with RASH3D. Based on the available information, it is not able to directly compare the simulation results of FLATMODEL and RASH3D with those of the other models in (a) above. In an effort to benchmark these two models, GEO has carried out a simulation using 3dDMM based on the same set of Voellmy parameters (i.e. $\phi = 25^o$ and $\xi = 1000$ m/s^2). The 3dDMM simulation predicts that the debris would take about 30 seconds to reach the bend at about CH 220 but the debris front almost stops at this location. This is very similar to the RASH3D's results. In the simulation of RASH3D, debris takes another 220 seconds to reach the actual final deposition location. However, 3dDMM does not produce the same results as RASH3D; the final debris runout of 3dDMM is about 40 m less (see Figure 4).

(e) Since debris profiles at different simulation times calculated by FLATMODEL were not submitted, no comparisons between FLATMODEL and 3dDMM can be made as above.

(f) The debris travelling time and maximum debris deposition thickness produced by FLO-2D were not reported; hence a comparison with others in these aspects cannot be made. Nevertheless, attention should be drawn to the fact that FLO-2D requires quite different inputs from the others in particular; it requires an inflow hydrograph at the landslide source area whereas an initial thickness of the landslide mass is specified for the other models. In the case of Tate's Cairn landslide, the inflow hydrograph is not available. To use FLO-2D to simulate this landslide case, NGI devised an inflow hydrograph based on DAN3D's results.

Tate's Cairn Landslide Forward Prediction

The following six sets of model parameters were provided to the participants for analysing the debris runout of a 10,000 m^3 landslide in the forward prediction exercise (see Table 11):

Table 11: Model parameters for Tate's Cairn landslide forward prediction

Case	Debris Entrainment Ratio	Voellmy Model Parameters	
		Apparent Friction Angle (°)	Turbulent Coefficient (m/s^2)
1(a)	100%	8^o	500
1(b)	0%	8^o	500
2(a)	100%	15^o	1000
2(b)	0%	15^o	1000
3(a)	100%	25^o	1000
3(b)	0%	25^o	1000

Not all the teams have attempted and presented all six cases. Table 12 summarises the modelling results received.

Table 12: Teams participating in modelling of Tate's Cairn landslide forward prediction

Team	Model	Case					
		1(a)	1(b)	2(a)	2(b)	3(a)	3(b)
Technical University of Catalonia	FLATMODEL	• (2)	•	• (2)	•	• (2)	•
GEO, Hong Kong	3dDMM *	•	•	•	•	•	•
UBC, Vancouver	DAN3D *	•	•	•	•	•	•
NGI, Norway	DAN3D (NGI) *	•	•	•	•	-	•
CEDEX, Madrid	Pastor(3)	-	-	-	-	-	-
Politecnico Di Torino	RASH3D	-	•	-	-(4)	-	•

Notes:

(1) • represents cases attempted and results presented.

(2) Only graphical outputs of erosion depth for Cases 1(a) and 3(a) are reported. No indication of deposition depth is presented in the graphical outputs, therefore a direct comparison with the other modelling results in terms of debris runout and debris flow path is not possible. Case 2(a) was reportedly attempted but results have not been given by the team.

(3) The team has adopted an initial landslide volume of 11052 m^3, $\phi = 16.7°$ (i.e. f = 0.3) and $\xi = 500$ m/s^2 in the forward prediction exercise, the results of which cannot be compared with those of the others that follow the given initial landslide volume and model parameters.

(4) Case 2(b) was reportedly attempted but the results have not been presented by the team.

Figures 5(a) and 5(b) show the debris flow paths and debris runout for (a)-series and (b)-series cases respectively. Tables 13(a) and 13(b) summarise the debris travelling times and maximum debris deposition depths of the (a)-series and (b)-series cases respectively.

Table 13(a): Summary of debris travelling times and maximum debris deposition depths in (a)-series

Case	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
1(a)	3dDMM	40	2.0 – 2.5
	DAN3D	-	2.0 – 3.0
	DAN3D(NGI)	-	6.1 – 8.0 ^
2(a)	3dDMM	60	4.5 – 5.0
	DAN3D	-	3.0 – 4.0
	DAN3D(NGI)	-	4.1 – 6.0 ^
3(a)	3dDMM	50	3.5 – 4.0
	DAN3D	-	1.0 – 2.0

Notes:

^ denotes the maximum debris depth (listed in the table for reference) but not the maximum deposition depth.

Table 13(b): Summary of debris travelling times and maximum debris deposition depths in (b)-series

Case	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
1(b)	FLATMODEL	-	11.6 ^
	3dDMM	50	2.0 – 2.5
	DAN3D	-	2.0 – 3.0
	DAN3D(NGI)		7.6 ^
	RASH3D	-	1.0 – 1.5
2(b)	FLATMODEL	-	8.2 ^
	3dDMM	60	3.5 – 4.0
	DAN3D	-	2.0 – 3.0
	DAN3D(NGI)	-	7.6 ^
3(b)	FLATMODEL	-	5.5 ^
	3dDMM	50	3.5 – 4.0
	DAN3D	-	1.0 – 2.0
	DAN3D(NGI)	-	~5 ^
	RASH3D	-	3.2

Notes:

^ denotes the maximum debris depth (listed in the table for reference) but not the maximum deposition depth.

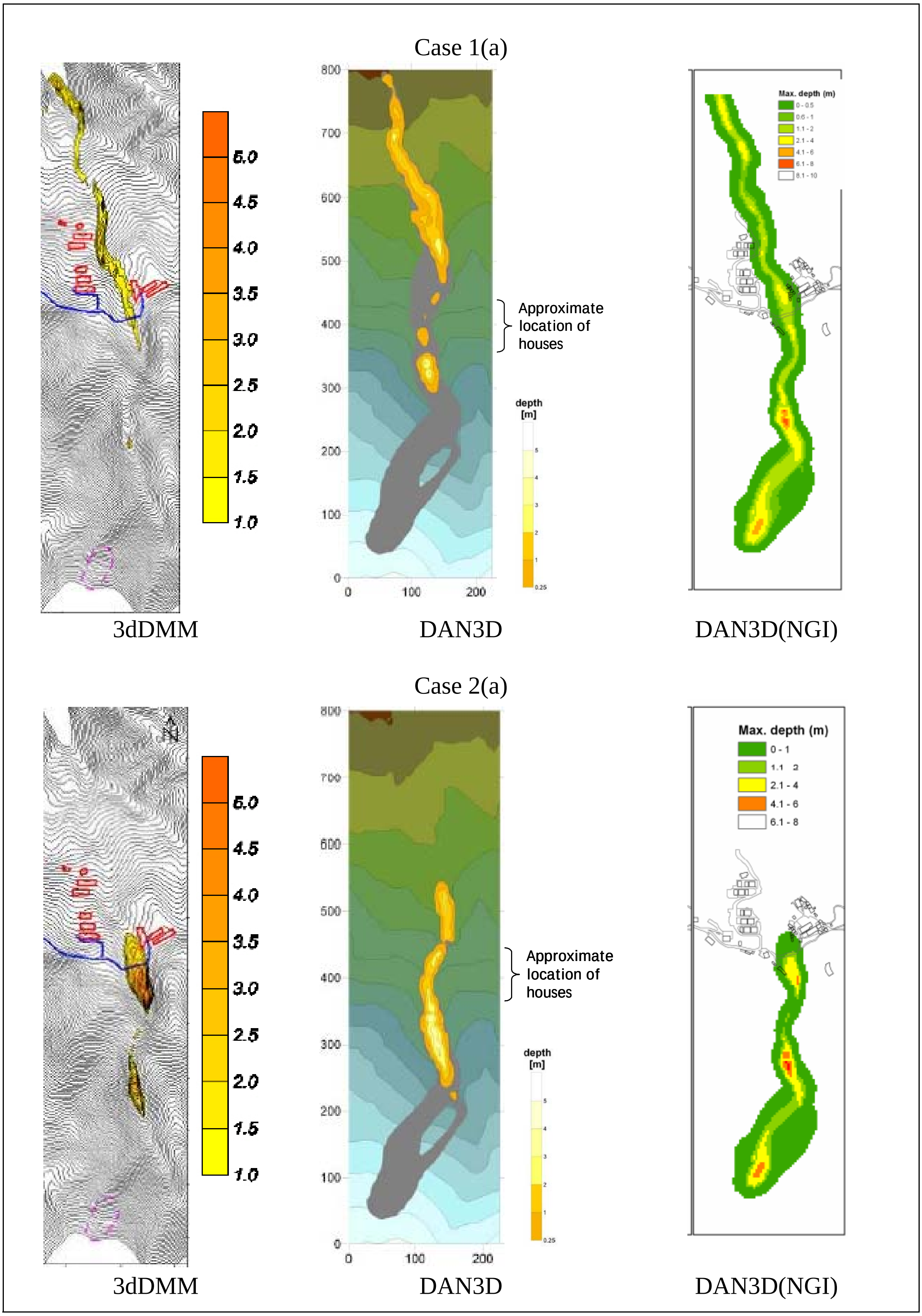


Figure 5(a): Simulation results by various models for Tate's Cairn landslide forward prediction

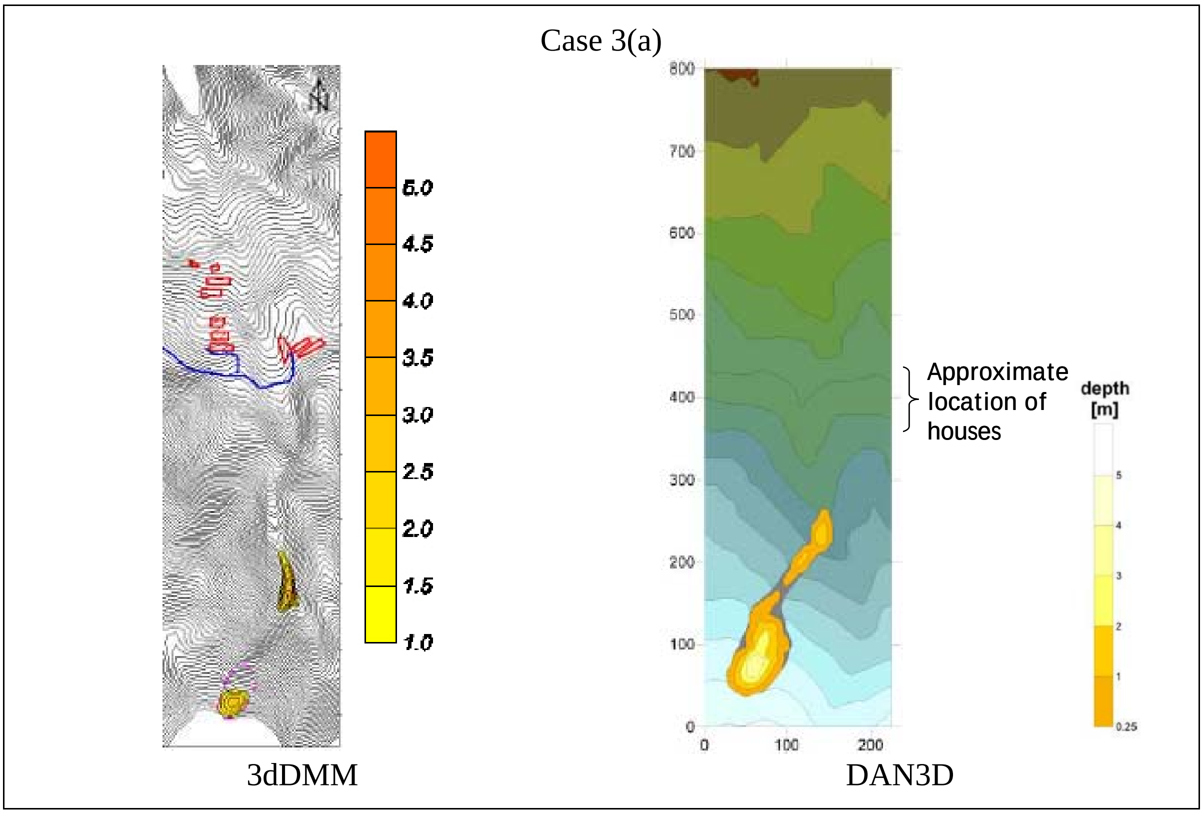


Figure 5(a) (Con't): Simulation results by various models for Tate's Cairn landslide forward prediction

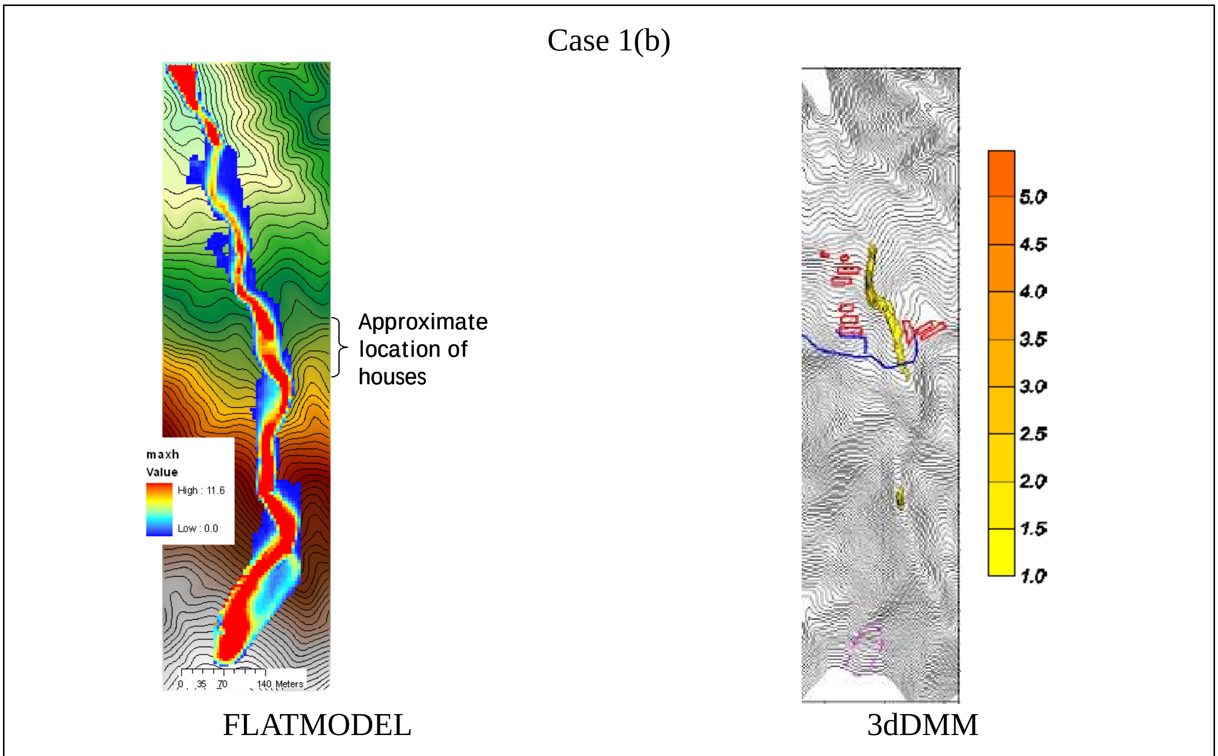


Figure 5(b): Simulation results by various models for Tate's Cairn landslide forward prediction

Case 1(b)

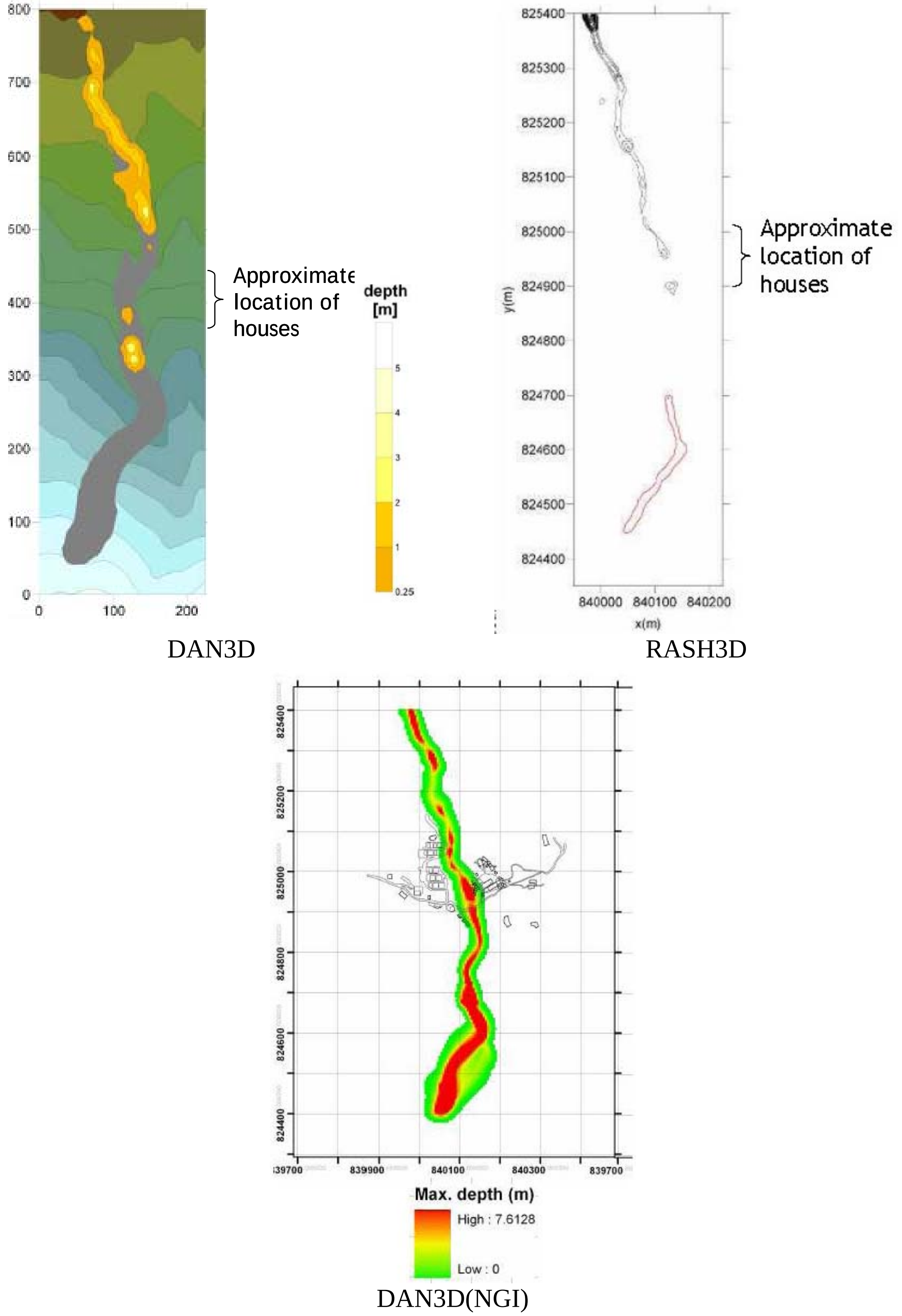


Figure 5(b) (Con’t): Simulation results by various models for Tate’s Cairn landslide forward prediction

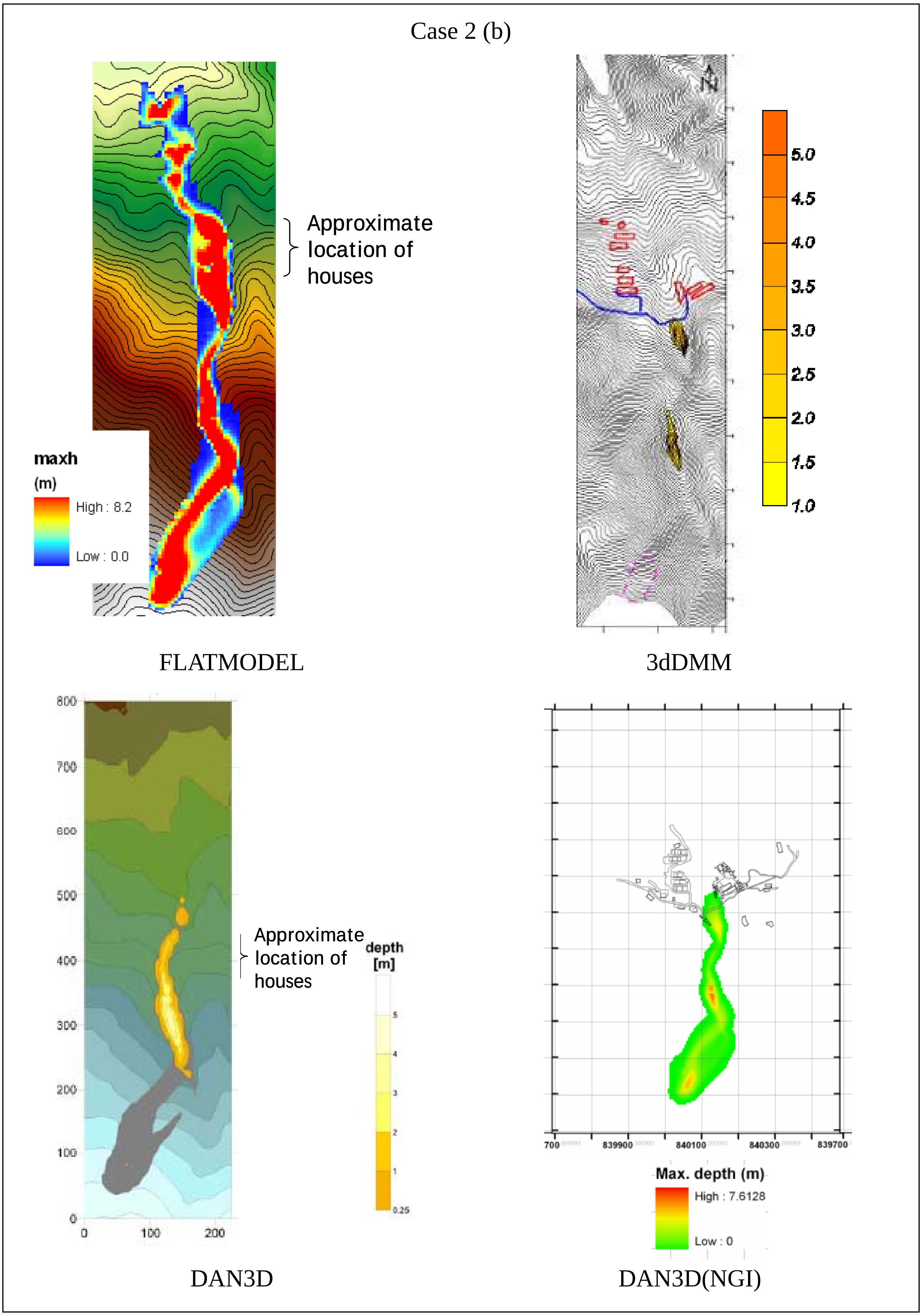


Figure 5(b) (Con't): Simulation results by various models for Tate's Cairn landslide forward prediction

Observations

(a) The modelling results of Cases 1(a) and 1(b) cannot be compared directly, as the frontal portion of the landslide, in all the models, has run out of the extent of the given modelling boundary. The predicted distal ends of the landslide have not been reported.

(b) Based on the modelling results of Cases 2(a), 2(b), 3(a) and 3(b) in terms of the overall runout of the debris and debris flow path, the three models marked * in Table 12 above, i.e. DMM, DAN3D and DAN3D(NGI), give similar simulation results, though there are some discrepancies in the maximum debris deposition depth among them.

(c) Only the 3dDMM team reports the debris travelling time, no other teams have reported on this. It is not therefore possible to provide comments on the debris runout time.

(d) The modelling results of FLATMODEL for Cases 2(b) and 3(b) indicate a longer runout distance as compared with those by 3dDMM, DAN3D and DAN3D(NGI).

Fei Tsui Road Landslide

Eight teams set up their dynamic models for simulation of Fei Tsui Road landslide. Six of the eight teams used pure frictional model in their simulations. The values of basal friction angle adopted by all the participants are very similar.

Table 14 summaries the teams and the model parameters adopted for simulation of Fei Tsui Road Landslide.

Table 14: Input parameters by different teams for Fei Tsui landslide

Team	Model	Friction Angle ϕ (°)
University of Alberta	Wang	Internal: 30 Basal: 30
University of Hong Kong	MADFLOW #	Internal: 35 Basal: 22
GEO, Hong Kong	3dDMM *	Internal: 35 Basal (at landslide scar): 22 Basal (elsewhere): 35
Universite Paris Diderot	SHALTOP-2D #	26
UBC, Vancouver	DAN3D *	Basal (on slope): 20 Basal (elsewhere): 35
CEDEX, Madrid	Pastor #	26.6
Kyoto University	Sassa-Wang	21.8 (1)
Politecnico Di Torino	RASH3D #	27

Notes:
(1) This is the initial basal friction. Since changes in the pore water pressure are considered by the model, the apparent friction angle at the base is subject to change during the course of simulation.

Figure 6 shows the debris flow paths and debris runout of the modelling results. A summary of the debris travelling times and maximum debris deposition depths are given in Table 15.

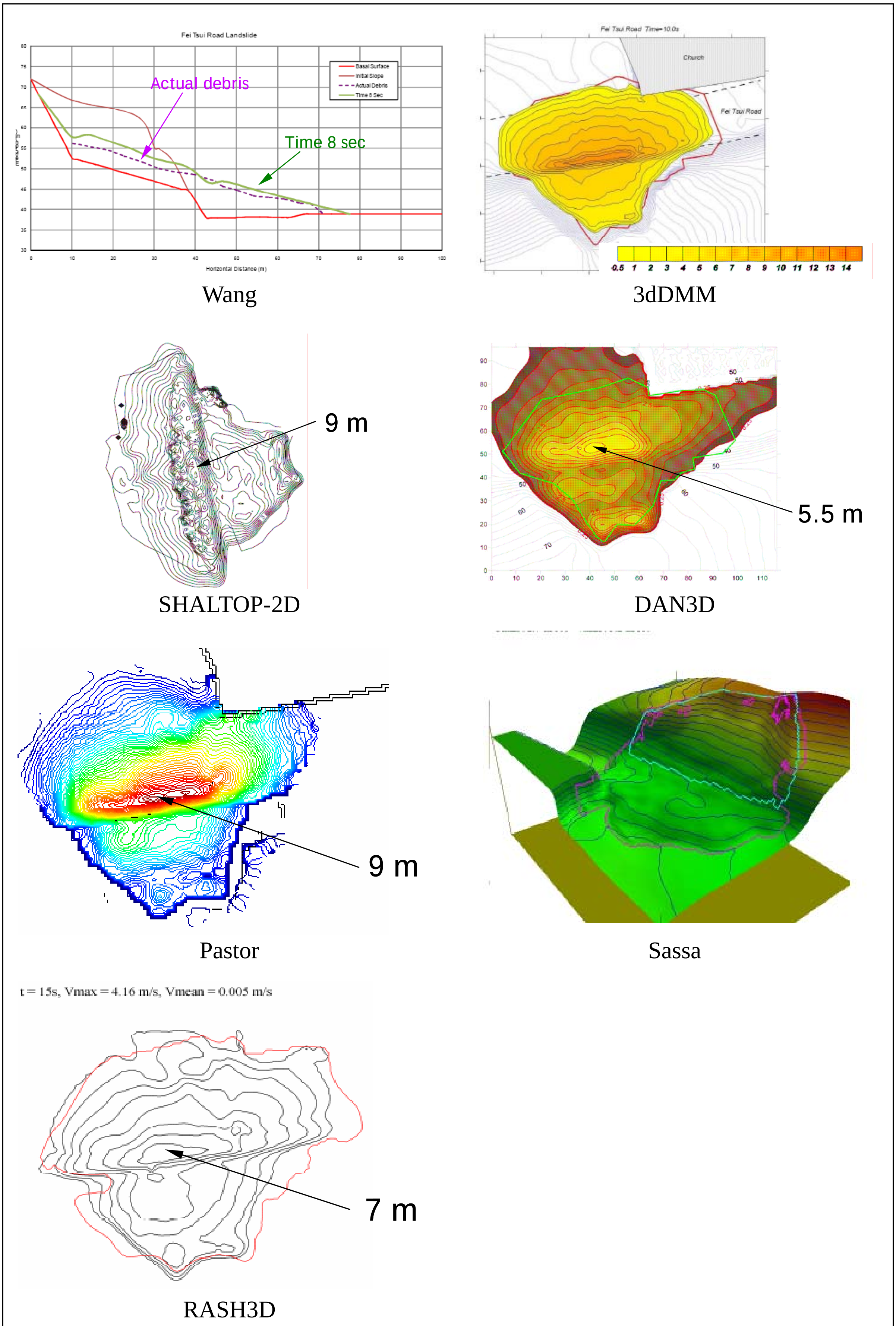


Figure 6: Simulation results by various models for Fei Tsui Road landslide

Table 15: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Depth (m)	
			Overall	At Church
University of Alberta	Wang	8	10	-
University of Hong Kong	MADFLOW	9	9	2
GEO, Hong Kong	3dDMM	10	10	3
Universite Paris Diderot	SHALTOP-2D	14	9	-
UBC, Vancouver	DAN3D	20	5.5	2.5
CEDEX, Madrid	Pastor	9	9	4.5
Kyoto University	Sassa-Wang	13	-	-
Politecnico Di Torino	RASH3D	15	8	-

<u>Observations</u>

(a) A direct comparison of the overall runout of the debris and debris flow path among the two models marked * in Table 14 above, i.e. 3dDMM and DAN3D, is possible as they use similar parameters. The two models perform similarly and give comparable simulation results, although DAN3D over-estimates the final deposition area within a thin debris thickness < 0.5 m.

(b) Similarly, the four models marked # in Table 14 above, i.e. MADFLOW, SHALTOP-2D, Pastor and RASH3D, give simulation results that match with well each other using similar basal rheology and parameters.

(c) A further examination of the models in (a) and (b) above indicates that their modelling results, in terms of the overall runout of the debris and debris flow path, resemble each other reasonably. Furthermore, the maximum debris deposition depths obtained by all the models do not deviate very much from each other, although some variations exist as are also noted in other benchmarking cases.

(d) It is noted that the rheological parameters adopted by Sassa-Wang's model is different from those adopted in other models. Sassa-Wang's model considers changes in the apparent friction angle due to consolidation. Apart from noting that the initial friction angle used by Sassa-Wang (i.e. 21.8^{o}) is lower than that by the others, further details on Sassa-Wang's model are not available for a more in-depth review.

Shum Wan Landslide

Results of two 2-D models and seven 3-D models of this landslide case were submitted by participants. One of the participating teams, University of Milano Bicocca and FEAT, submitted both 2-D and 3-D modelling results produced by the model TOCHNOG. The list of participants and the model parameters used are presented in Table 16.

Table 16: List of participants and the input parameters for Shum Wan landslide

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Alberta	Wang	Internal: 30 Basal: 16	-
University of Hong Kong	MADFLOW *	20	
University of Milano Bicocca and FEAT	TOCHNOG	2-D: 22 – 26 3-D: 20 – 22	-
GEO, Hong Kong	3dDMM *	Internal: 38 Basal: 40 (shipyard) 15 (elsewhere)	-
		Internal: 38 Basal: 40 (shipyard) 15 (elsewhere)	500
Universite Paris Diderot	SHALTOP-2D *	18	
UBC, Vancouver	DAN3D *	22	-
		11.3	200
CEDEX, Madrid	Pastor	16.7	1000
Kyoto University	Sassa-Wang	21.8 (1)	-

Notes:
(1) This is the initial basal friction. Since changes in the pore water pressure are considered in the model, the apparent friction angle at the base is subject to change during the course of simulation.

Figure 7 shows the debris flow paths and the final debris deposition profiles of the different models. Table 17 summarises the debris travelling times and maximum debris deposition depths.

Table 17: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Alberta	Wang	20	~9
University of Hong Kong	MADFLOW	30	5.0
University of Milano Bicocca and FEAT	TOCHNOG	2-D: 20 3-D: 50	2-D: ~9 3-D: 11.0
GEO, Hong Kong	DMM	Frictional: 28 Voellmy: 24	7.0 – 8.0
Universite Paris Diderot	SHALTOP-2D	28	7.0 – 8.0
UBC, Vancouver	DAN3D	-	5.0 – 6.0
CEDEX, Madrid	Pastor	29	8.0
Kyoto University	Sassa-Wang	26	-

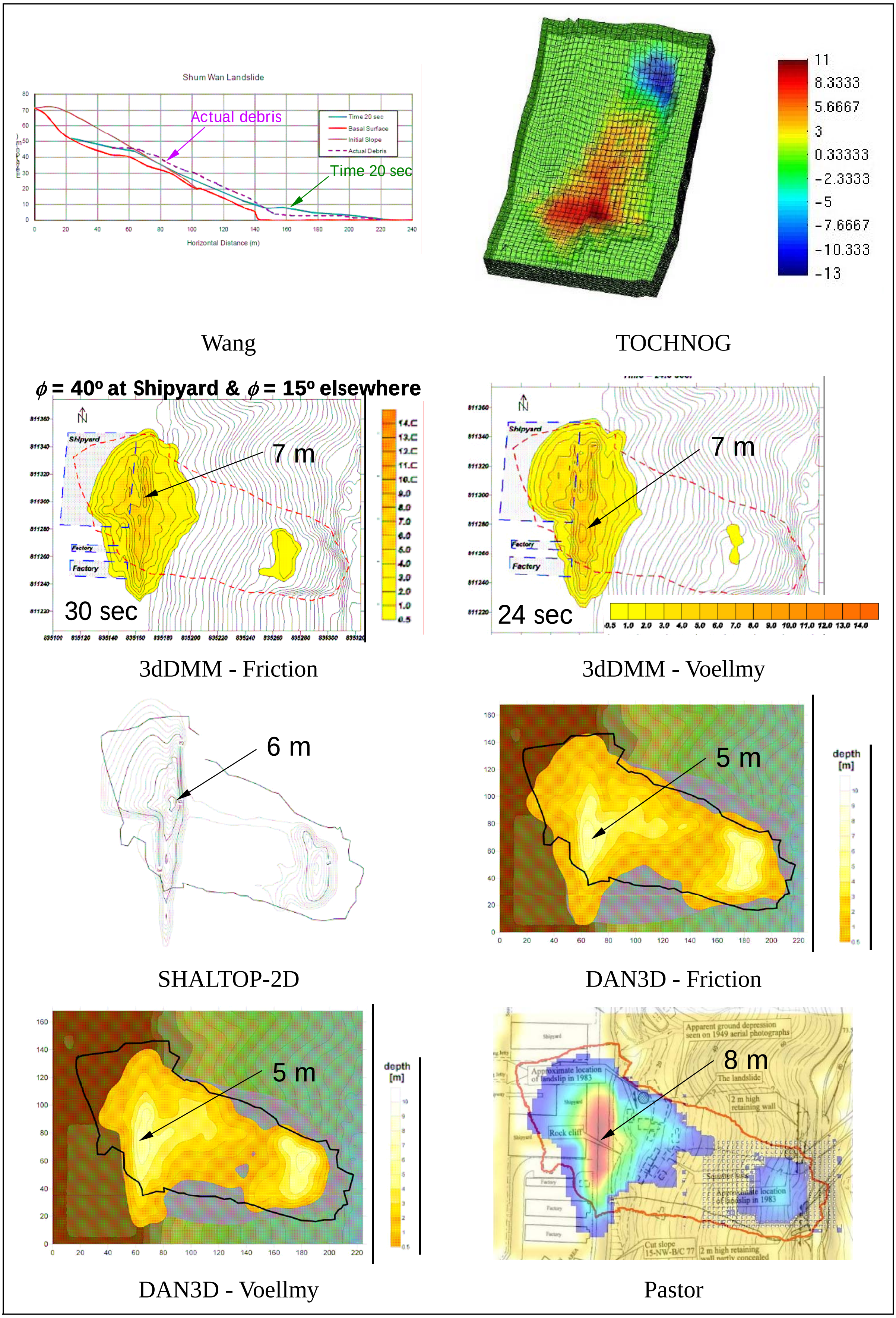
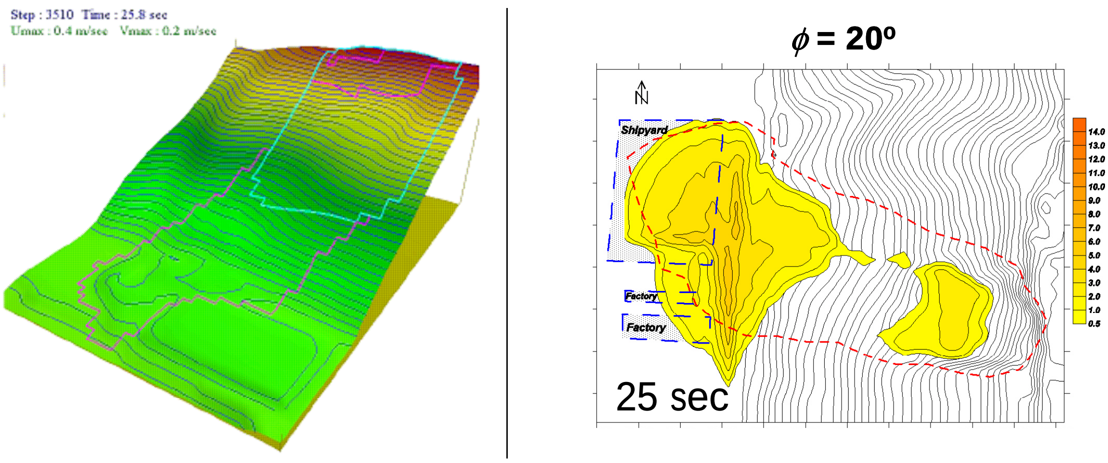


Figure 7: Simulation results by various models for Shum Wan landslide



Sassa

3dDMM - Friction

Figure 7 (Con't): Simulation results by various models for Shum Wan landslide

Observations

(a) Figure 7 indicates that the four models marked * in Table 16, i.e. MADFLOW, 3dDMM, DAN3D and SHALTOP-2D, give similar modelling results in terms of the overall runout of the debris and the broad shape of debris deposition. The debris flow paths and the maximum debris deposition depth are also comparable with each other.

(b) The simulation results of TOCHNOG in terms of the overall runout of the debris and the broad shape of debris deposition resemble those produced by the 3-D models in (a). Nevertheless, the debris travelling time and the maximum debris deposition depth are slightly greater than those of the models in (a). Little information on the exact debris travelling time/velocities is available in this landslide case, and hence it cannot be further assessed which of the models have simulated a more accurate travelling time.

(c) The simulation results produced by the 2-D models TOCHNOG and Wang are very similar in terms of the debris travelling time, the maximum deposition depth and runout distance. However, direct comparison of the results of the two models is not possible, since the two models adopt very different calculations of internal stress and energy dissipation. In addition, TOCHNOG simulates the conditions of failure of the groundmass without using the depth-averaged shallow-flow assumption, which is by nature different from the method adopted by Wang and other integrated approach models.

(d) The overall runout of the debris simulated by Sassa-Wang's model appears to be comparable with the models in (a) and (b) above. However, since details such as the final deposition depth are not reported, further comparisons on other aspects are not possible.

(e) GEO has also simulated the landslide with 3dDMM using a frictional basal rheology with $\phi = 20°$ apart from those reported before the Forum. The results are given in the paper submitted separately for publication in the Forum Proceedings. The simulated deposition profile of this additional analysis is also shown in Figure 7. With this basal rheology, the modelling results in terms of the overall runout of the debris and the broad shape of debris deposition of 3dDMM can be compared directly with those of MADFLOW, DAN3D and SHALTOP-2D, which have adopted similar basal rheology and material parameters.

Frank Slide

Nine teams submitted their simulation results of the Frank Slide. Seven of them used frictional rheology in their simulations, while the other two teams used Voellmy rheology. Table 18 shows the participants and the parameters adopted.

Table 18: List of participants and the input parameters for Frank slide

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Milano Bicocca and FEAT	TOCHNOG	Internal: 25 Basal: 12 (source area) Basal: 16 (other areas)	-
GEO, Hong Kong	3dDMM *	Internal: 40 Basal: 12	-
Universite Paris Diderot	SHALTOP-2D *	12	-
UBC, Vancouver	DAN3D #	Basal: 15° (source area) Basal: 5.7° (f = 0.1) (path)	Source Area: N/A Path: 500
CEDEX, Madrid	Pastor *	12.4 (f = 0.22)	-
Vienna University of Technology	PFC	-	-
Kyoto University	Sassa-Wang	36.9 (f = 0.75)	-
Politecnico Di Torino	RASH3D #	5.7	700
University at Buffalo, New York	TITAN2D *	14	-

The debris flow paths and debris runout of the different models are presented in Figure 8. Table 19 summarises the debris travelling times and maximum debris deposition depths given by the models.

Table 19: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Milano Bicocca and FEAT	TOCHNOG	90	25 – 30
GEO, Hong Kong	3dDMM	60	15 – 20
Universite Paris Diderot	SHALTOP-2D	100	45 – 50
UBC, Vancouver	DAN3D	-	20 – 25
CEDEX, Madrid	Pastor	71	25 – 30
Vienna University of Technology	PFC	80	-
Kyoto University	Sassa-Wang	120	-
Politecnico Di Torino	RASH3D	60	25 - 30
University at Buffalo, New York	TITAN2D	55	20 - 25

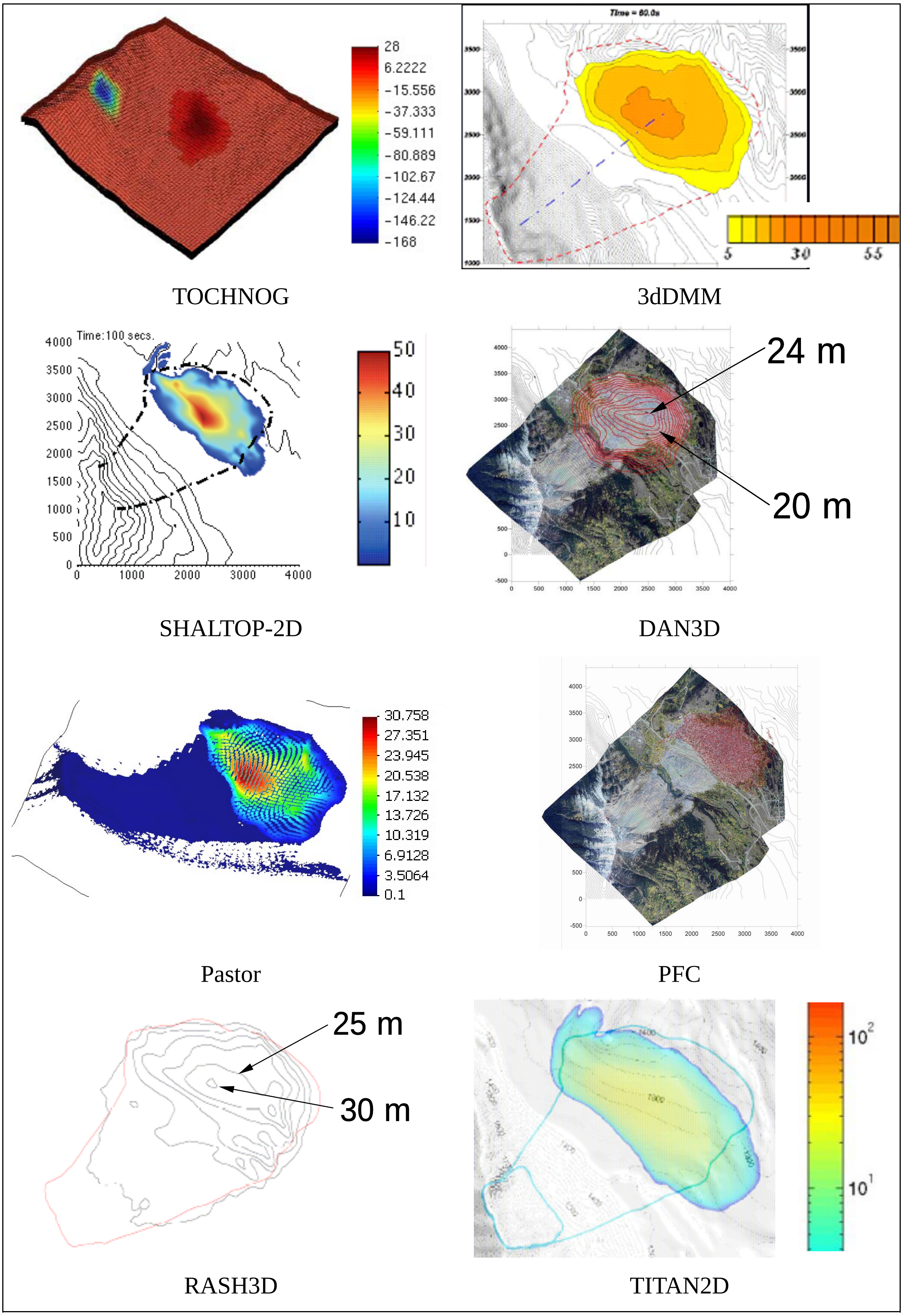
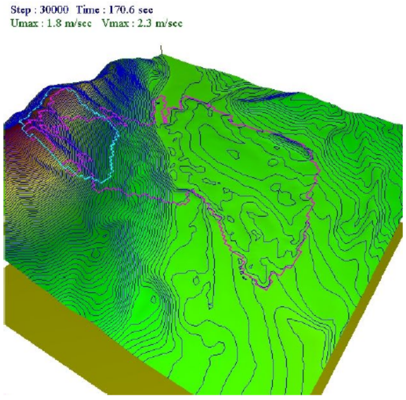


Figure 8: Simulation results by various models for Frank Slide



Sassa

Figure 8 (Con’t): Simulation results by various models for Frank Slide

Observations

(a) For models that adopt frictional basal rheology, the models marked * in Table 18, i.e. 3dDMM, SHALTOP-2D, Pastor and TITAN2D, give modelling results that resemble each other in terms of the overall runout of the debris and the broad shape of debris deposition.

(b) Similarly, for models that adopt Voellmy basal rheology, the models marked # in Table 18, viz. DAN3D and RASH3D, give comparable modelling results in terms of the overall runout of the debris and the broad shape of debris deposition.

(c) The modelling results of TOCHNOG (which adopts an elasto-plastic rheology for the landslide mass elements) appear to match with those of the models in (a) above. (Note: The outline of the simulated debris deposition zone given in Fig. 5 of the paper by the TOCHNOG team submitted to the Forum Proceedings also shows a good match with the actual landslide.)

(d) The modelling results in the form of cluster of particles produced by PFC enable only a comparison of the extent of the debris deposition with the other models, as the rheological and energy dissipation models adopted are different from those adopted in other models. The overall runout of the debris as well as debris travelling time resembles that of the other models. No comment can be made for maximum debris deposition depth as related information has not been provided in the PFC submission.

(e) A review of the modelling results of Sassa-Wang’s model is difficult, as the submission does not contain sufficient details for comparison.

Sham Tseng San Tsuen Debris Flow

Five teams attempted this case. NGI used two 3-D models, DAN3D and RAMMS, to carry out simulations of the debris flow. They tried two sets of Voellmy parameters when using RAMMS, and they also set up DAN3D models using frictional and Voellmy rheologies. Participants who attempted the case and the model parameters used are summarised in Table 20.

Table 20: List of participants and the input parameters for Sham Tsang San Tsuen debris flow

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Alberta	Wang	Internal: 35 Basal: 20	-
NGI, Norway	RAMMS – V (1) #	14	450
	RAMMS – V (2)	Basal: 8.2 (exposed rock) 0.6 (waterfall) 31 (houses & nullah) 14 (elsewhere)	450
	DAN3D(NGI) – V #	14	450
	DAN3D(NGI) – F *	Internal: 35 Basal: 19.3	-
GEO, Hong Kong	3dDMM	Internal: 30 Basal: 12	500
UBC, Vancouver	DAN3D – F *	17	-
	DAN3D – V #	16.7 (f = 0.3)	500
CEDEX, Madrid	Pastor *	20	-

Figure 9 shows the debris flow paths and debris reaches submitted by the participants. Table 21 presents the debris travelling times and maximum debris deposition depths.

Table 21: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Alberta	Wang	30	~7
NGI, Norway	RAMMS – V (1)	-	0.5 – 1.0
	RAMMS – V (2)	-	1.0 – 1.5
	DAN3D(NGI) – V	-	1.5 – 2.0
	DAN3D(NGI) – F	-	1.0 – 1.5
GEO, Hong Kong	3dDMM	50	1.5 –2.0
UBC, Vancouver	DAN3D – F	-	0.5 – 1.0
	DAN3D – V	-	1.0 – 1.5
CEDEX, Madrid	Pastor	-	-

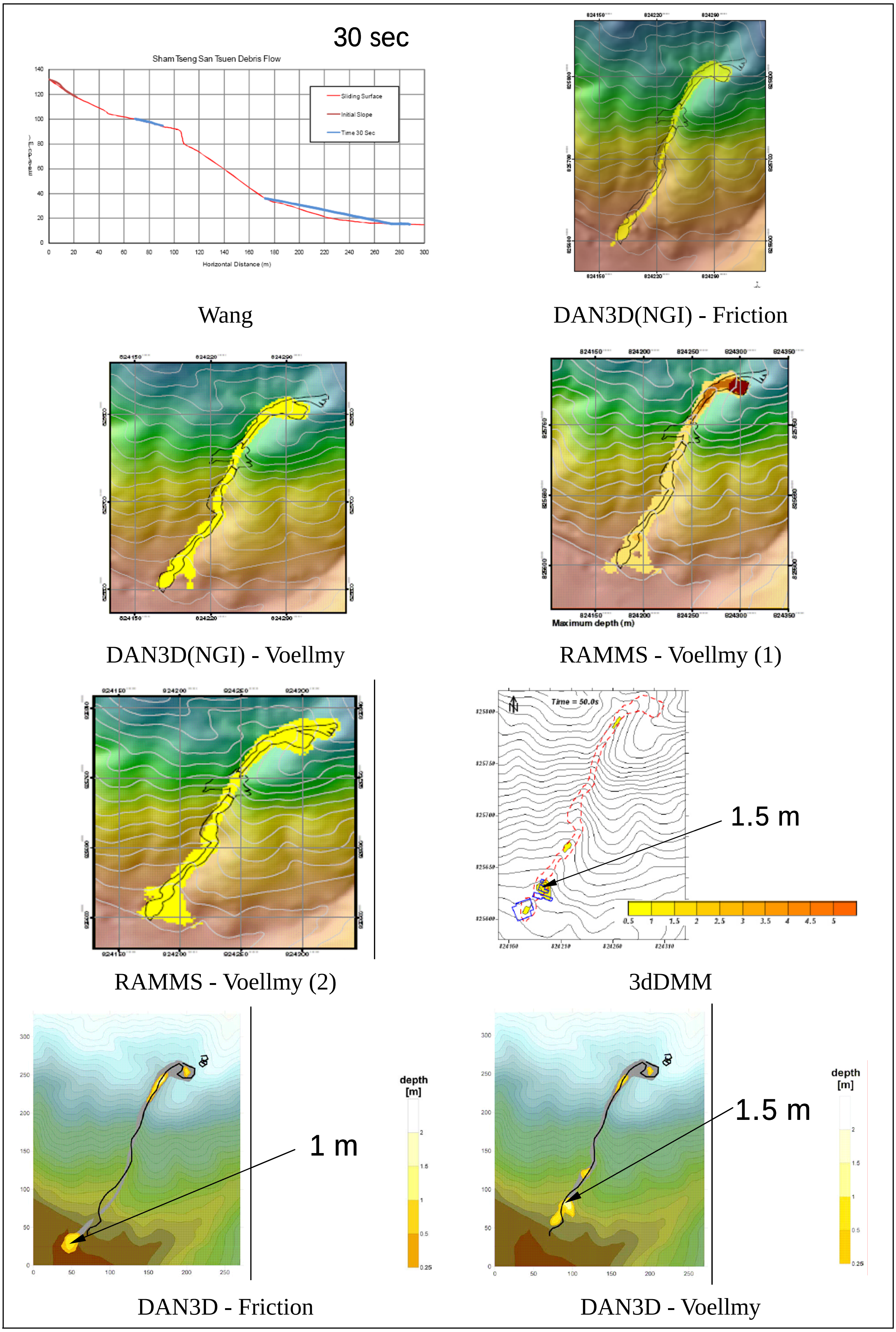
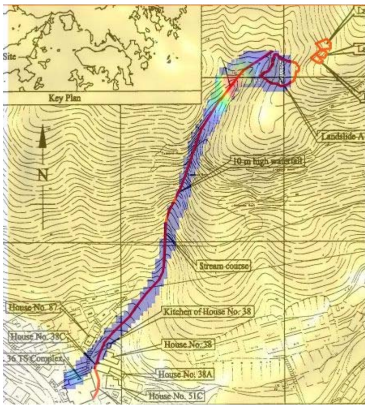


Figure 9: Simulation results by various models for Sham Tseng San Tsuen debris flow



Pastor

Figure 9 (Con't): Simulation results by various models for Sham Tseng San Tsuen debris flow

<u>Observations</u>

(a) The friction rheological parameters adopted in the models marked * in Table 20, viz. DAN3D(NGI), DAN3D and Pastor, are in similar order. This facilitates direct comparison among their modelling results. Figure 9 indicates that their modelling results are comparable with each other in terms of the overall runout of the debris and the broad shape of debris deposition.

(b) The Voellmy rheological parameters adopted in the models marked # in Table 20, viz. RAMMS, DAN3D(NGI) and DAN3D, are in similar order. A comparison of their modelling results based on Figure 9 shows that the models produce similar results, which have consistence in terms of the overall runout of the debris and the broad shape of debris deposition.

(c) In terms of the geometry of debris deposition, the simulated results of Wang's model are notably different from that of the other models in the group. This may be related to the fact that Wang's 2-D continuum model does not allow for separation of debris, whereas the other 3-D models permit this.

1990 Tsing Shan Debris Flow

Amongst the five teams that produced simulations of the 1990 Tsing Shan debris flow, four teams adopted Voellmy rheology, while Wang's model used pure frictional rheology with explicit consideration of energy loss due to internal shear distortion. Table 22 summarises the participants and the parameters used in the models.

Table 22: List of participants and the input parameters for 1990 Tsing Shan debris flow

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Alberta	Wang	Internal: 35 Basal: 24	-
Technical University of Catalonia	FLATMODEL	11.3	64 [(1)]
GEO, Hong Kong	3dDMM	Internal: 30 Basal: 15	500
UBC, Vancouver	DAN3D	11.3	500
CEDEX, Madrid	Pastor	10.2	500

Notes:

(1) This is calculated based on the reported Chezy coefficient of 8 $m^{1/2}/s$. The square of the Chezy coefficient is equivalent to the Voellmy coefficient.

Figure 10 presents the debris flow paths and debris runout given by the above models. Table 23 summarises the debris travelling times and maximum debris deposition depths.

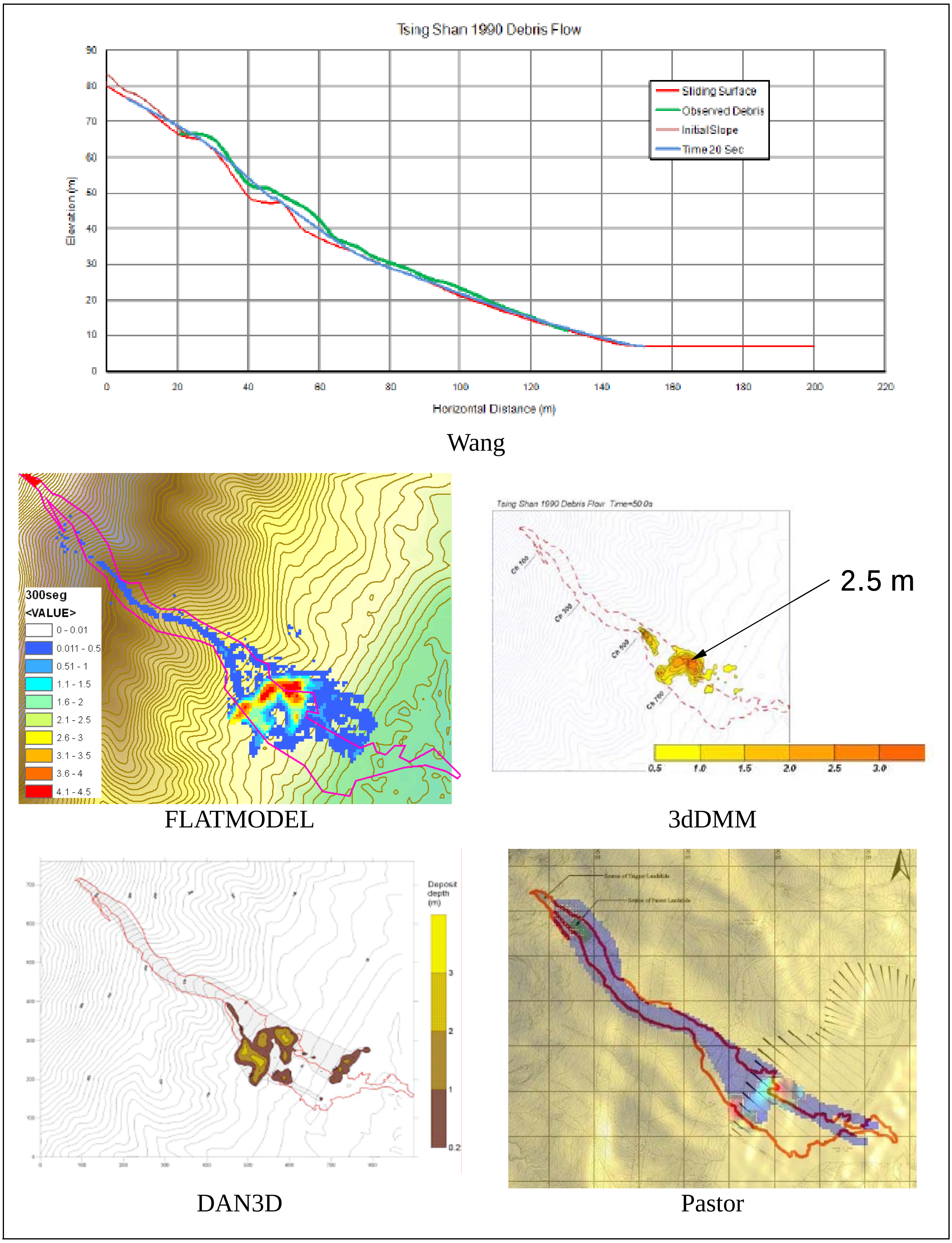


Figure 10: Simulation results by various models for 1990 Tsing Shan debris flow

Table 23: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Alberta	Wang	-	-
Technical University of Catalonia	FLATMODEL	-	4.0 – 4.5
GEO, Hong Kong	3dDMM	50	2.5 – 3.0
UBC, Vancouver	DAN3D	-	2.0 – 3.0
CEDEX, Madrid	Pastor	81	-

Observations

(a) This case involves the simulation of entrainment effect along the debris flow path in order to accumulate the landslide source volume to its final landslide volume at deposition.

(b) It is noted that the approaches adopted by the different teams in simulating the entrainment effect are dissimilar with each other and therefore, there are notable differences among the modelling results submitted. These make direct comparison among them difficult. However, it is evident that the different assumptions made on the mode of debris entrainment in the models affected the simulation results.

2000 Tsing Shan Debris Flow

Three teams used 3-D model to simulate the 2000 Tsing Shan debris flow, which bifurcated at the top of a ridge line. The 2-D model of Wang was used for simulation of the debris flow, for which the participant set up two dynamic models to simulate the runout behaviours of each of the branches. A list of participants and parameters used are given in Table 24.

Table 24: Input parameters by different teams for 2000 Tsing Shan debris flow

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Alberta	Wang	14	-
Technical University of Catalonia	FLATMODEL *	8.53	400 (1)
GEO, Hong Kong	3dDMM *	Pylon Area: 45 Other Areas: 11	500
CEDEX, Madrid	Pastor *	10.2 (f = 0.18)	500
Notes: (1) This is calculated based on the report Chezy coefficient of 20 m$^{1/2}$/s.			

Figure 11 shows the debris flow paths and debris runout. The debris travelling times and the maximum debris deposition depths estimated by the different model are given in Table 25.

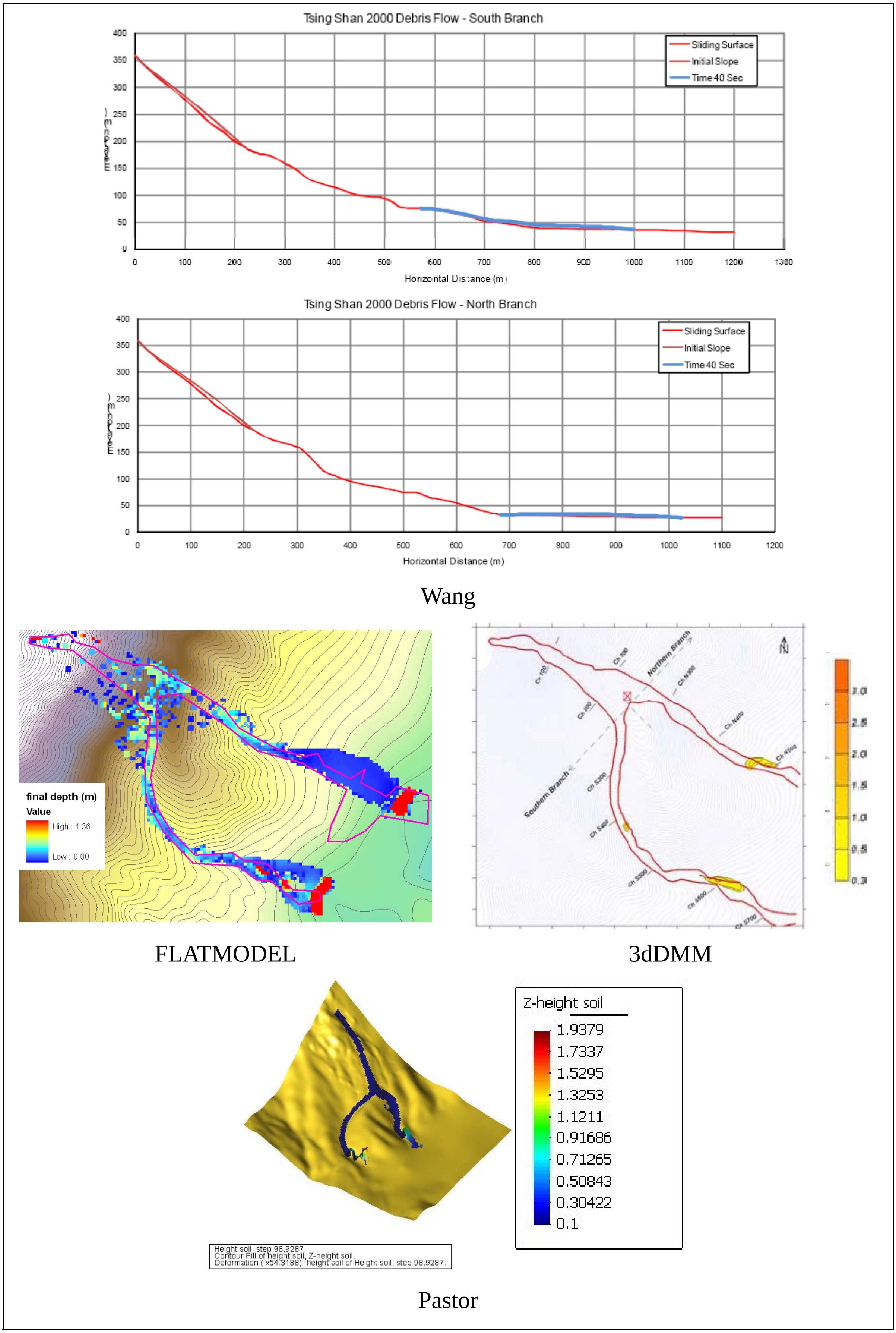


Figure 11: Simulation results by various models for 2000 Tsing Shan debris flow

Table 25: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Alberta	Wang	40	-
Technical University of Catalonia	FLATMODEL	-	1.0 – 1.5
GEO, Hong Kong	3dDMM	25	1.0 – 1.5
CEDEX, Madrid	Pastor	81	1.5 – 2.0

<u>Observations</u>

(a) The 2000 Tsing Shan debris flow is included to examine the capability of the models in simulating debris flows over complex topography, including bifurcation of debris trail.

(b) Notwithstanding the basal rheology and material parameters adopted, the models marked * in Table 24 above, i.e. FLATMODEL, 3dDMM and Pastor, have successfully simulated the bifurcated debris trails.

(c) 3dDMM and Pastor give reasonable modelling results of the overall runout of the debris. The modelling results of FLATMODEL show a larger final deposition area, which is not observed by the other models.

Thurwieser Rock Avalanche

Five continuum models and one discrete particle model were used to set up the simulation model for this case. To reflect the varying frictional characteristics along the debris trail, which comprises glacier, together with steep and hummocky rocky terrain, all the continuum models apply different frictional parameters for different regions in the calculation domain. Table 26 presents a list of participants and the parameters used.

Table 26: List of participants and the input parameters for Thurwieser rock avalanche

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Hong Kong	MADFLOW	Region 1: 10 (1) Region 2: 20	500
University of Milano Bicocca and FEAT	TOCHNOG	Landslide Material: 40 Failure Surface: 26 Topo. Surface (glacier): 3 Topo. Surface (debris): 22	-
GEO, Hong Kong	3dDMM *	Glacial Area: 12 Other Areas: 27	-
UBC, Vancouver	DAN3D *	Source Area: 25 - 28 Glacial Area: 5.7 (f=0.1) Below Glacial Area: 28	Source Area: N/A Glacial Area: 1000 Other Area: N/A
CEDEX, Madrid	Pastor *	Glacial Area: 0 Other Areas: 21.3 (f = 0.39)	Glacial Area: 1000 Other Areas: N/A
Vienna University of Technology	PFC	-	-

Notes:
(1) Region 1 is above elevation 2600 m a.s.l. where rock outcrop exists.

The graphical results of the different models are presented in Figure 12. Table 27 summaries the results.

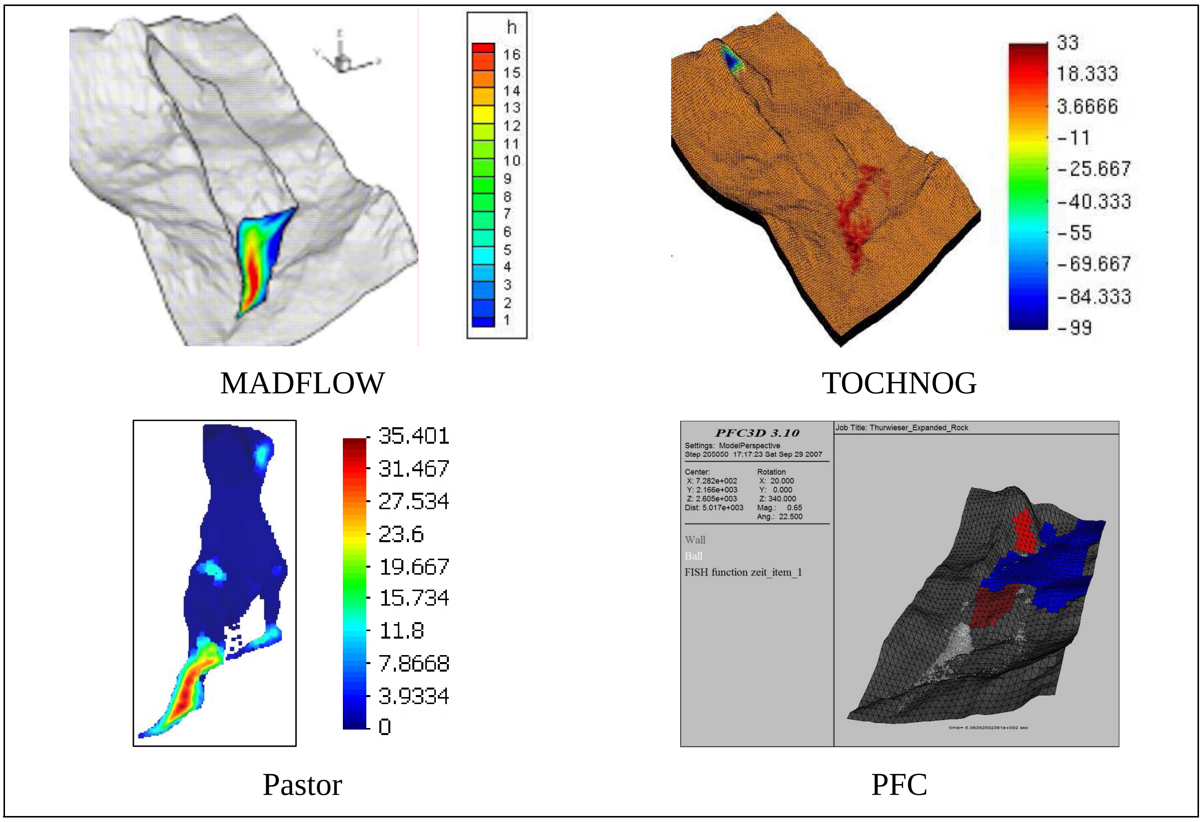
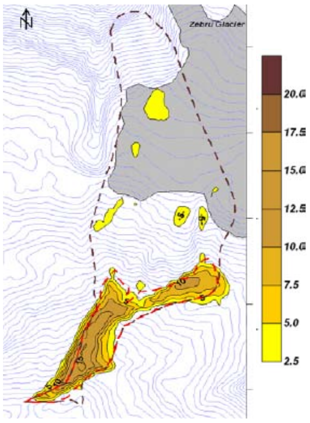
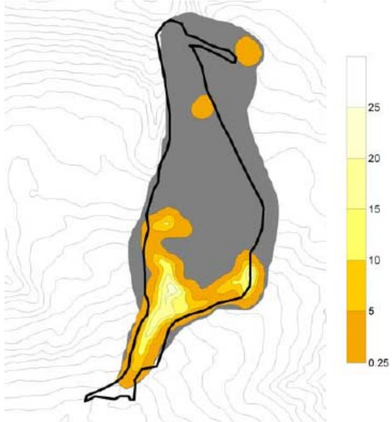


Figure 12: Simulation results by various models for Thurwieser rock avalanche



3dDMM



DAN3D

Figure 12 (Con't): Simulation results by various models for Thurwieser rock avalanche

Table 27: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Hong Kong	MADFLOW	300	15 – 20
University of Milano Bicocca and FEAT	TOCHNOG	100	15 – 20
GEO, Hong Kong	DMM	100	15 – 20
UBC, Vancouver	DAN3D	-	20 – 25
CEDEX, Madrid	Pastor	684	30 – 35
Vienna University of Technology	PFC	500	-

Observations

(a) This is a complicated back-analysis case in terms of modelling different types of ground materials over which the debris travels and their related basal rheology, and developing a digital elevation model that has sufficiently good resolution to reflect reasonably the changes in the complex topography.

(b) Because of (a) above, the models have, based on their respective capability in 3-D modelling, adopted different sets of material properties and basal rheology to simulate the landslide. Thus, a direct comparison of their modelling results is difficult.

(c) Notwithstanding (a) and (b) above, it is noted that, based on the orders of the adopted input parameters, the models marked * in Table 26, i.e. 3dDMM, DAN3D and Pastor, have produced consistent modelling results in terms of the overall runout of the debris and debris flow path. In particular, branches of the debris at the source and at the toe are observed in their modelling results, indicating their capabilities in modelling debris flow over complex terrain. The simulations results also match well with the actual landslide.

(d) The modelling result of MADFLOW does not exhibit debris branches along the debris flow paths. This may possibly be due to the fact that the model has no provisions for splitting up connectivity among debris elements in their formulations.

(e) PFC also produces modelling results that resemble the landslide. It gives the debris branches of debris at the source.

Lo Wai Debris Flood

One set of 2-D and one set of 3-D simulation results of Lo Wai debris flood were submitted. Table 28 summaries the participants and parameters used. The results of the debris flood travelling times and maximum deposition depths are presented in Table 29.

Table 28: List of participants and the input parameters used for Lo Wai debris flood

Team	Model	Friction Angle ϕ (°)	Turbulent Coefficient ξ (m/s^2)
University of Alberta	Wang	Internal: 30 Basal: 9	-
CEDEX, Madrid	Pastor	(1)	(1)

Notes:
(1) Pastor used a combined rheological model involving Bingham and Manning rheology. In general, the basal friction adopted by the Pastor's model is the lesser of the Bingham and the Manning frictions.

Table 29: Summary of debris travelling times and maximum debris deposition depths

Team	Model	Debris Travelling Time (s)	Maximum Debris Deposition Depth (m)
University of Alberta	Wang	40	~4
CEDEX, Madrid	Pastor	200 – 300	~3

Observations

On the basis that both of the above models adopted different rheologies, a direct comparison between the two models is not possible. Apart from the rheological models, the initial conditions specified in the models are probably different, as Wang's model requires the input of a thickness of landslide mass at the source rather that inflow hydrograph, as it should be for this case involving overflow from a catchwater. These could be the reasons for the remarkable difference between the debris flow travelling times estimated by the two models. The time given by Wang's simulation is one order of magnitude less than that of Pastor's model.

SUMMARY OF BENCHMARKING RESULTS

(a) Four 3-D models that allow for frictional and Voellmy basal rheologies, viz. DAN3D, 3dDMM, Pastor and RASH3d, have consistently provided similar modelling results for a range of cases in the benchmarking exercise (Table 30). In terms of the debris runout path, travel distance, time and overall shape of the debris deposition, the simulation results from these models match reasonably well with the analytical/experimental results of the calibration cases as well as the field behaviour of the actual landslide cases. Similarly, in a number of cases where the frictional rheology is adopted, SHALTOP-2D and MADFLOW also give results that are consistent with the four models. This is promising in view of the different 3-D numerical solution methodologies adopted by the models.

(b) TOCHNOG, RAMMS and TITAN2D provided modelling results in this benchmarking exercise on a relatively smaller number of cases. The modelling results of RAMMS are similar to those of the models described in (a) above (Table 30). The results of TOCHNOG and TITAN2D are also comparable, although there appear to be some discrepancies when compared with the simulation results of the other models. However, since the simulation results of TOCHNOG, RAMMS and TITAN2D for more cases in this benchmarking exercise are not available, it is not possible to further compare their results with those of other models in this exercise.

(c) Despite the apparently good fit of the simulation results from the models discussed in (a) and (b) above on the debris runout path, travel distance, time and overall shape of debris deposition, there are some notable discrepancies in the spatial extent and profile of the debris deposition zones as simulated by the models. The discrepancies may be related to the assumptions made in respect of the internal stress within the debris and the different approaches for 3-D numerical solution adopted by the different models.

(d) In evaluating the benchmarking results, apart from examining the debris runout paths and deposition zones, consideration should also be given to whether the simulated debris runout durations and velocities match with those of the actual cases. This has been considered as far as information is available from the benchmarking results provided by the participants and from the actual verification and landslide cases. However, since the participants have not been requested to extract the modelling results at specific time intervals of the simulated debris runout, direct comparison of the temporal distributions of the simulated reach and velocity of the debris among the participants, and with the actual verification and landslide cases, is difficult. This is an area for improvement in future benchmarking exercises.

(e) The simulation results of FLATMODEL and Sassa-Wang also match the debris runout and the broad extent of deposition zone, although some differences to the results of the other models are noted. For example, the deposition extents estimated by FLATMODEL appear to be larger as compared with the others for cases such as the Tate's Cairn debris flow. On the other hand, a complete benchmarking of Sassa-Wang model with others cannot be made since details such as the final deposition depth of the models are not reported.

(f) Many of the models have previously been tested or calibrated with other cases and the results published separately. These results have not been further reviewed in this benchmarking exercise, and the observations made in this report are based on the modelling results on the benchmark cases submitted to this exercise.

(g) Submissions were received from the use of three other models, which are by nature quite different to the other 3-D models described above:
   - PFC – The simulation results are available for a small number of cases. The simulated debris runout path and the overall shape of debris deposition resemble those of the actual landslides. Direct comparison with other models cannot be made due to the different rheological and energy dissipation assumptions adopted.

- FLO-2D – This was used for the Tate's Cairn debris flow. The participants have not reported the use of other models for the simulation of the other landslide cases.

- Wang (i.e. University of Alberta) – This 2-D model includes consideration of energy changes associated with shear distortion of the debris. A direct comparison with the simulation results by the other 3-D models, the experimental results and the actual landslides is difficult given the 2-D nature of Wang's model. In addition, the different boundary/source conditions assumed in Wang's model have affected the results in some cases. Where comparison has been made, it suggests that Wang's simulation results appear to be different from those of the other models with similar basal rheological parameters. This reflects possible differences of Wang's model from the other models, including its consideration/assumption of energy dissipation due to shear distortion of the debris.

(h) In general, it is noteworthy that the use of a 3-D model has distinct advantages in simulating the source, runout flow path and deposition zone, which are 3-D in geometry. A number of numerical solution techniques can be applied, and these appear to be giving consistent results as observed in this Benchmarking Exercise. Some models allow for separation and merging of debris along the runout path, which is required in dealing with more complicated cases. In comparison, the allowance for entrainment is generally less well developed. The modes of entrainment assumed in the modelling can greatly affect the simulation results. Some models (e.g. Pastor, DAN3D, 3dDMM and FLATMODEL) allow for entrainment effects based on entrainment rates prescribed by users or empirical rules, while TECHNOG and PFC simulates erosion and deposition based on the material properties and the type of interaction with the topographic surface and material along the runout path.

(i) None of the models allows for changes in the terrain profile as a result of debris deposition and entrainment during the simulation, which may in some cases affect the debris flow path and the modelling results.

(j) By nature, models that are based on depth-averaged shallow-flow solution are not suitable for use in simulating landslide with very steep failure surface or where the debris thickness is large in comparison with the runout distance. In practice, it is normally not a problem in modelling mobile debris flows and long runout landslides.

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APPENDICES

Appendix A – Landslide Runout Analysis Benchmarking Exercise: Terms of Reference

Table 32: Summary of modelling results

Team	Model Denoted As	Group A			Group B				Group C					
		Dam Break	Deflected Sand Flow	USGS Flume test	Shum Wan Landslide	Fei Tsui Road Landslide	1990 Tsing Shan Debris Flow	Sham Tseng San Tsuen Debris Flow	Frank Slide	Thurwieser Rock Avalanche	2000 Tsing Shan Debris Flow	Tate's Cairn Landslide	Tate's Cairn Landslide Forward Prediction	Lo Wai Debris Flood
University of Alberta	Wang	●	●	●	●	●	●	●			●	●		●
University of Hong Kong	MADFLOW		●		●	●				●				
University of Milan	TOCHNOG	●			●				●	●				
NGI, Norway	RAMMS							●						
	DAN3D(NGI)							●				●	●	
	FLO-2D(NGI)											●		
Technical University of Catalonia	FLATMODEL	●		●			●				●	●	●	
GEO, Hong Kong	3dDMM	●	●	●	●	●	●	●	●	●	●	●	●	
Universite Paris Diderot	SHALTOP-2D	●		●	●	●			●					
	RASH3D(Paris)	●												
UBC, Vancouver	DAN	●				●	●							
	DAN3D		●		●	●	●	●	●	●		●	●	
CEDEX, Madrid	Pastor	●	●	●	●	●	●	●	●	●	●	●	●	●
Vienna University of Technology	PFC								●	●				
Kyoto University	Sassa				●	●			●					
Politecnico Di Torino	RASH3D		●			●			●			●	●	
University at Buffalo, New York	TITAN2D		●						●					

Note: ▭ represents similar modelling results from the models when similar rheology models and parameters are adopted.

APPENDIX A
LANDSLIDE RUNOUT ANALYSIS BENCHMARKING EXERCISE: TERMS OF REFERENCE

1. Introduction

Prediction of landslide motion distance and velocity is required for hazard and risk assessment and for design of risk mitigation measures. The goal of such predictions is to estimate the area that may be affected by the movement of a potential landslide and to map hazard intensity parameters, esp. velocity, depth of flow and thickness of deposits.

The technology for making such predictions has advanced substantially in recent years. Numerical computer-based models now exist, capable of simulating the motion of a given volume of unstable material from its source on a hillside to a deposition area. As the technology begins to mature, it is useful to compare the various models with one another. The Organizing Committee of the 2007 International Forum on Landslide Disaster Management, Hong Kong have decided to devote a one-day session at the Forum to a review of the current state-of-the-art of landslide dynamics modelling. The main subject of the session will be the presentation of the results of a Benchmarking Exercise, as described below. The session programme for this subject will include a theme lecture, selected presentations from the participants of the Benchmarking Exercise, a summary of the results by the Review Committee, and a round-table discussion.

The Benchmarking Exercise is not a competition! Its purpose is to assess whether this emerging field of science is on its way towards establishing some degree of commonality amongst different methods used by various groups. It is felt that forward runout predictions can only be regarded as sufficiently reliable once there is certain convergence of modelling philosophies and methodologies amongst various groups specializing in the subject.

2. The Benchmarking Exercise

2.1 Data to be supplied to Participants

The organizers have selected nine examples of landslides and one laboratory test involving the flow of dry sand. A dam-break scenario, for which analytical solutions exist, is also included in the Benchmarking Exercise. All the cases involve long-runout landslides or mobile debris floods, moving at extremely rapid velocities. The exercise does not include slow-moving slides such as earth flows, nor does it include fragmental rock fall or rigid movements of relatively intact blocks of rock.

In consideration of the degree of complexity of the landslide dynamics, the cases are grouped as follows:

<u>Group A - Calibration cases</u>

1. Dam-break scenario
2. Laboratory test of dry sand flow prepared by Swiss Federal Institute of Technology, Lausanne
3. USGS flume test

Group B - Less sophisticated cases

4. Shum Wan Landslide, Hong Kong
5. Fei Tsui Road Landslide, Hong Kong
6. Sham Tseng San Tsuen Debris Flow, Hong Kong
7. 1990 Tsing Shan Debris Flow, Hong Kong

Group C - More sophisticated cases

8. Frank Slide, Canada
9. Thurwieser Rock Avalanche, Italy
10. 2000 Tsing Shan Debris Flow, Hong Kong
11. Tate's Cairn Landslide, Hong Kong
12. Lo Wai Debris Flood, Hong Kong

Data available for each of the cases includes the following:

(1) DEM-PATH: A digital elevation model of a rectangular area on the slope, encompassing the outline of the landslide rupture surface, path and deposition area (or a contour map showing the elevations of the pre-landslide topography).

(2) DEM-SOURCE: A DEM representing the vertical thickness map of the landslide source (or a contour map showing the elevations of the post-landslide topography; for the debris floods, the inflow hydrograph of the debris flow will be given, along with debris concentration and the specified location of the inflow). Source volume is understood here as the volume between the rupture surface and the original pre-slide ground surface. Both DEM's will be represented by regular grids of elevations, referenced to the same point of origin and with equal grid spacing and extent. Thus, adding DEM-SOURCE to DEM-PATH would produce a digital elevation model of the pre-failure slope surface. Note, in case of landslides that begin by sliding, the source thickness DEM has not yet been increased by a factor allowing for volume increase due to fragmentation.

(3) A brief description of the landslide. The description will include surficial and bedrock geology, engineering-geological description of the materials forming the landslide source, runout path and deposit, areal distribution of different material covers along the runout path, comments on groundwater and surface water, land use and weather at the time of occurrence. Average volumetric bulking of the source material during detachment will be suggested. A number of photographs of each site will be provided. References for detailed site-specific landslide study reports, where available, are given.

(4) A map showing the outline of the final landslide deposits and the outline of any material entrainment areas along the runout path. Where possible, thickness distribution of final deposits and entrainment zones eroded by the landslide will be provided in the form of contours, or at least as spot values.

(5) A summary of all existing information regarding the behaviour of the landslide will be given, particularly observed or estimated movement velocities or movement duration, as far as available.

2.2 The Analysis

The participants are invited to assemble a dynamic model for each of the selected cases, based on the above information. The appropriate rheological type (or model) and the corresponding material properties of the flowing mass are to be selected by each participating group based on an optimized back-analysis.

For the case at Tate's Cairn (No. 11), in addition to undertaking a back-analysis of the 2005 debris flow, the participants are additionally invited to undertake a forward prediction of debris travel distance, debris velocity and runout paths for an impending failure involving the detachment of about 10000 m^3 of material from the distressed hillside given the presence of significant tension cracks on the hillside above the 2005 landslide source area. The results of the forward prediction are of relevance for the assessment of the necessary risk mitigation measures to protect the road and village houses below the distressed hillside. The forward prediction may be done in a deterministic or probabilistic manner. The case provides an opportunity for testing the capability of different modelling techniques and benchmarking the modelling results. Two years ago, this case posed a challenge to engineers in Hong Kong in an emergency situation. After the Tate's Cairn Landslide in 2005, detailed investigation revealed that there could be an impending failure involving a 10000 m^3 detachment from the distressed hillside. Debris mobility modelling was undertaken to establish the possible extent of potential consequence of this impending failure and provided useful information for the design of our emergency response actions.

2.3 Output

The participants should provide detailed plots of the flowing mass at intervals during motion and after stoppage. Further, they should provide summaries of movement velocities and direction vectors at various times. They should provide a brief discussion of each case specifying the rheological models and parameters used in the optimized back-analyses and any special provisions or assumptions used in the analyses.

The participants should further provide a brief description of the theory used in their models, with appropriate references. Also useful would be information on the computing resources used, e.g. computer, operating system, programming language and amounts of computing resources involved.

The output results should be summarized in succinct, illustrated reports on each case history. The reports may be in electronic (.pdf format) or hard copy.

The output data will be used by the selected participants to prepare their presentations at the Forum and by the Review Committee in preparing its summary report, which will also be presented at the Forum.