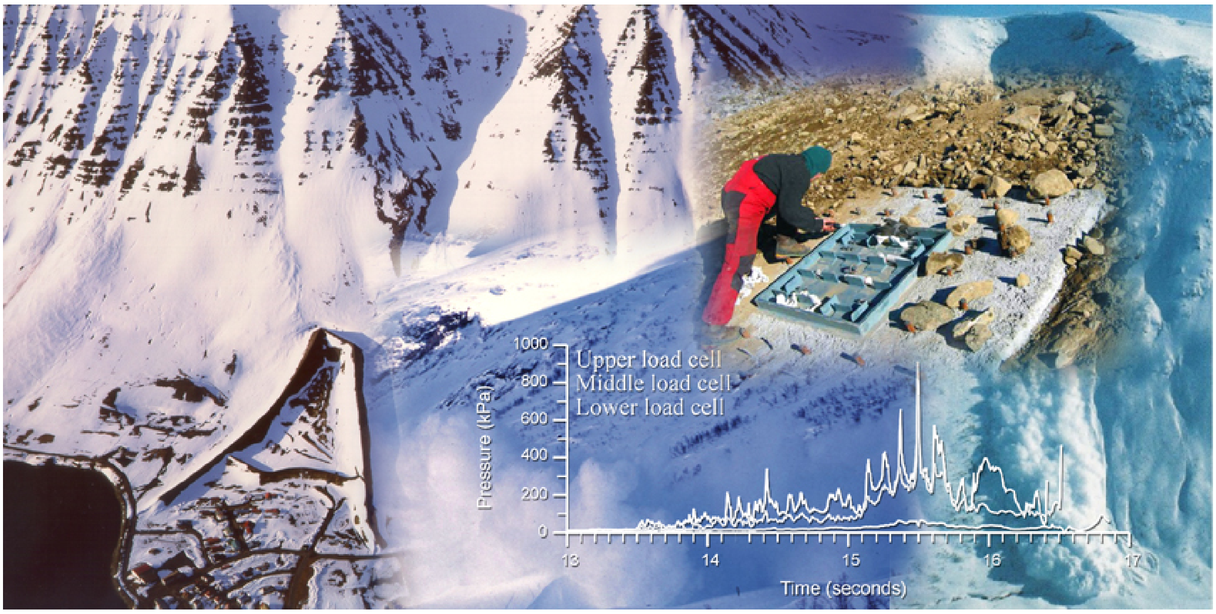
European Commission — *Fifth Framework Programme*

SATSIE

Avalanche Studies and Model Validation in Europe

EU Contract no. EVG1–CT2002–00059



Final Report

Contains Sections 1–6

Deliverable D19

Reporting period: 1st October 2005 – 31st May 2006

Coordinator: Karstein Lied, Norwegian Geotechnical Institute

Project home page: http://www.leeds.ac.uk/satsie

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Chapter 1

Management Progress Report 01/10/2005–31/05/2006

1.1 Objectives of the reporting period

Sensor development and installation: Test the repaired FMCW radars in the Ryggfonn path and the improved snow rheometer at Col du Lac Blanc during the winter 2005/2006.

Development of data analysis methods: Improve existing analysis methods for seismic signals, in particular for the determination of avalanche velocities at Ryggfonn. Further develop analysis methods for high-time-resolution load-cell measurements from the Vallée de la Sionne test site (in collaboration with SLF).

Experiments and data analysis: Conduct full-scale measurements at Ryggfonn, wait for events on the instrumented deflection dams at Flateyri and Taconnaz. Conduct further experiments on the rheology of rapidly flowing granular materials and avalanche–dam interaction at the granular chute in Pavia and with snow at the Col du Lac Blanc chute. Analyse data from Ryggfonn and from chutes.

Development of new dynamical models: Continue development, validation and documentation of ETNA's MN2L model. Complete the formulation of NGI's model D2FRAM, implement it as 1D and 2D codes, begin validation process and write documentation.

Dissemination of results: Complete the handbook on dam design. Preparatory stage of the European Summer University advanced course on snow avalanche modelling (to be held after the conclusion of SATSIE). Continue maintenance of the website and complete data archiving.

1.2 Scientific/technical progress in the Work Packages

1.2.1 WP 1 – Sensor development

- The four repaired frequency-modulated continuous-wave (FMCW) profiling radars deteriorated again after a few weeks. Installation of new antennas did not solve the problem. Work has been ongoing to determine the reason of the malfunctioning.

- Rapid formation of shear bands persisted in ETNA's improved annular snow rheometer. Unless a further modification that keeps the membrane pressure constant upon compression of the snow proves successful in the future, this rheometric concept will have to be abandoned.

- After the likely cause of the malfunctioning of the five-transducer air pressure sensors had been identified, a report detailing the conclusions and a proposal for further improvements have been written.

1.2.2 WP 2 – Data analysis techniques

- The algorithms for analysing radar data (Doppler and FMCW) have been made operational.
- Due to difficulties in obtaining SLF's impact-pressure data from Vallée de la Sionne, this task had to be abandoned.
- The seismically dissipated energy of a Ryggfonn avalanche could be determined and was found to be in agreement with the size classification obtained by means of field observations.
- Significant progress has been made in developing tests for detecting changes in the statistical properties of noisy signals, based on comparing the actual data to surrogate data with the same mean and variance. The method is being applied to detecting flow-regime transitions in granular flows.

1.2.3 WP 3 – Instrumentation of selected facilities

- The four FMCW radars were reinstalled in the Ryggfonn path. Later on, the antennas were exchanged with an improved design. One of the instruments was damaged in the process.
- At the end of the reporting period, UB-DGG's seismic instruments were repatriated to Barcelona.

1.2.4 WP 4 – Measurement campaigns

- After a winter unusually poor in snow on the Norwegian west coast, an artificial release was attempted at Ryggfonn in early May 2006, but the avalanche stopped before reaching the uppermost sensors. Thus only video footage and seismic data were obtained.
- The snow-chute measurements at Col du Lac Blanc were extended to a large variety of snow types. From these data, the rheological properties were determined.
- Impact experiments were continued at the granular chute in Pavia and the snow chute at Col du Lac Blanc. The experiments with snow onto a deflection dam do not seem to agree with the theoretical expectations based on the theory of granular shocks, which had been confirmed earlier with dry granular material in the Bristol experiments.

1.2.5 WP 5 – Model development

- The velocity profiles measured in the chute experiments at Col du Lac Blanc have been implemented in MN2L.
- Formulation of D2FRAM, NGI's new flow-regime changing model, has been largely completed. For lack of a reliable three-dimensional theory of stress generation in a sheared granular medium, corresponding results from 2D studies are tentatively used. Two alternative forms for the density evolution equation can be used. More work is required to include the effects of the bed curvature in a consistent yet efficient way. The numerical implementation has been delayed for a number of reasons and will be developed further beyond the end of the project.

- Work on powder snow avalanche modelling concentrated on relatively simple centre-of-mass models with fixed shape but variable size, for which analytic solutions can be found in certain cases. They were tested against measurements at Vallée de la Sionne and video data from flume experiments.
- Theoretical analyses for shock formation and supercritical overflow during avalanche–dam interaction have been further developed and validated with observations from natural snow avalanches in Norway, Iceland and France, and formulated as design criteria for avalanche dams for the SATSIE dam design handbook (Task 6.4). Field data, laboratory experiments and existing design guidelines about impact pressures have also been analysed and formulated in terms of explicit design guidelines for use in the handbook.

1.2.6 WP 6 – Data sharing and dissemination of results

- The *SATSIE homepage* was kept up-to-date.
- *Archiving* of experimental data using CDF as the data format has been completed.
- *Handbook on dam design:* A draft version of the entire document (except for a few sections) has been written. The final version could not be produced within the project duration because interaction within the handbook writing team during the formulation of the new design criteria and collaboration with the SLF in Davos took longer than anticipated. The handbook will be finalised later in the year 2006.
- *European Summer University, advanced course on avalanche modelling:* External financing for an advanced course on avalanche hazard mapping could not be secured in time for the autumn of 2006, it will therefore be offered in the autumn of 2007. An organising committee has been appointed, and PGRN will provide logistic and administrative support.

1.3 Milestones and deliverables

Note: The “Status” column in Table 1.1 reflects the status of the milestones at the end of the reporting period: 3 – achieved; 2 – nearing completion; 1 – not yet near completion.

The following milestones were reached during the last eight months of SATSIE:

M0.7: The 3rd Annual Report was delivered to the Commission on time.

M0.8, M0.9: The Technology Implementation Plan and the Final Report are completed within the two months after the conclusion of SATSIE on 31 May 2006.

M1.13, M2.5: The high-frequency impact pressure data from Vallée de la Sionne were not made available to DAMTP. The report, delivered together with the Final Report, therefore does not include such analysis and software.

M3.7, M3.8: The reports on the European avalanche research facilities (Deliverable D8)and on the installations carried out during SATSIE (Deliverable D10) are delivered together with the Final Report.

M4.10: The Deliverables D11 (Summary publication on results from small and large-scale experiments) and D12 (Summary publication on avalanche / dam interaction measurements) have been completed and are delivered together with the Final Report. D11 is at the same time a draft version of a review paper to be published in a peer-reviewed journal in the near future. A scientific paper

Table 1.1: Project planning and time table – List of milestones (starting date 01.10.2002)

No.	Date	Content	Tasks	Status
M0.1	30.04.2003	Deliverable D1 (Management Progress Report #1)		3
M0.2	30.11.2003	Deliverable D3 (1st Annual Report)		3
M0.3	30.04.2003	Deliverable D4 (Management Progress Report #2)		3
M0.4	30.10.2004	Deliverable D5 (Midterm review meeting)		3
M0.5	30.11.2004	Deliverable D7 (2nd Annual Report)		3
M0.6	30.04.2005	Deliverable D9 (Management Progress Report #3)		3
M0.7	30.11.2005	Deliverable D16 (3rd Annual Report)		3
M0.8	31.07.2006	Deliverable D17 (Technology Implementation Plan)		3
M0.9	31.07.2006	Deliverable D19 (Final Report)		3
M1.1	31.08.2002	Shear/normal stress plates ready for tests	T1.5	3
M1.2	31.10.2002	Prototype LED sensors ready for tests	T1.4	3
M1.3	31.10.2003	Snow rheometer ready for tests	T1.6	3
M1.4	30.09.2003	Video locations and recording strategies selected	T1.2	3
M1.5	31.12.2003	Seismic equipment ready for tests	T1.7	3
M1.6	15.12.2003	Prototype frequency-stepping radar ready for first tests	T1.1	3
M1.7	31.10.2003	Prototype pulsed Doppler radar ready for basic testing	T1.1	3
M1.8	30.09.2002	Shear/normal stress plates ready for installation	T1.5	3
M1.10	31.12.2002	LED sensor arrays ready for installation	T1.4	3
M1.11	30.10.2004	Improved design of frequency-stepping radar	T1.1	3
M1.12	30.06.2004	Prototype pulsed Doppler radar ready for operational use	T1.1	3
M1.13	30.11.2004	Deliverable D6 (together with WP 2)	T1.1–1.7	3
M2.1	31.12.2002	Review of current techniques, proposals for improvements	T2.1–2.6	3
M2.2	31.05.2003	Beta software and algorithms for data analysis completed	T2.1–2.6	3
M2.3	31.07.2003	Review of data analysis with proposals for improving measurements	T2.1–2.6	3
M2.4	31.05.2004	Version 1 of software and algorithms for data analysis completed	T2.1–2.6	3
M2.5	30.11.2004	Deliverable D6 (together with WP 1)	T2.1–2.6	3
M2.6	31.07.2004	Review of data analysis, proposals for improving measurements	T2.1–2.6	3
M2.7	31.05.2005	Version 2 of software and algorithms for data analysis completed	T2.1–2.6	3
M3.1	30.09.2003	Inventory of needed measurements and existing instrumentation	T3.1–3.5	3
M3.2	30.09.2003	Inventory of the existing laboratory facilities	T3.4–3.5	3
M3.3	30.09.2003	Plan for extended instrumentation of the Ryggfonn site	T3.1–3.5	3
M3.4	31.10.2003	Instrumentation maintenance after winter 2003	T3.1–3.3	3
M3.5	31.10.2004	Instrumentation maintenance after winter 2004	T3.1–3.3	3
M3.6	30.11.2004	Installation of instrumentation at Ryggfonn completed	T3.1–3.5	3
M3.7	30.11.2004	Deliverable D8: Updated overview of European test sites	T3.1–3.5	3
M3.8	31.08.2005	Deliv. D10: Documentation of installation work	T3.1–3.5	3
M3.9	30.09.2005	Instrumentation maintenance after winter 2005	T3.1–3.3	3
M4.1	31.05.2003	Summary of experiments during winter 2003	T4.1–4.4	3
M4.2	31.07.2003	Preliminary analysis and comparison of updated experimental plan	T4.1–4.4	3
M4.3	30.11.2004	Exp. data from winter 2003 processed and archived	T4.1–4.3	3
M4.4	30.10.2004	Chute experiments 2003 summarised, processed and archived	T4.4	3
M4.5	31.05.2004	Summary of experiments during winter 2004	T4.1-T4.3	3
M4.6	31.07.2004	Preliminary analysis and comparison – updated experimental plan	T4.1–4.4	3
M4.7	30.11.2004	Exp. data from winter 2004 processed and archived	T4.1–4.3	3
M4.8	30.05.2005	Chute experiments 2004 processed and archived	T4.4	3
M4.9	31.05.2005	Summary of experiments during winter 2005	T4.1–4.3	3
M4.10	31.03.2006	Deliverables D11, D12	T4.4–4.5	3
M4.11	31.12.2005	Chute experiments 2005 processed and archived	T4.4	3
M4.12	31.05.2006	Summary of experiments during winter 2006	T4.1-T4.3	3
M5.1	30.06.2004	Preliminary reports on model development	T5.1–5.4	3
M5.2	31.12.2004	Updated reports on model development	T5.1–5.4	3
M5.3	31.03.2006	Summary report on the validation of the new models	T5.5	3/1
M5.4	31.03.2006	Deliverable D13 (new models of specific processes	T5.1–5.4	3/2
M6.1	31.01.2003	Deliverable D1: SATSIE web site established	T6.3	3
M6.2	31.03.2004	Data format for SATSIE data archive defined	T6.1	3
M6.3	30.11.2004	Preprocessed data from winter 2003 archived	T6.2	3
M6.4	30.11.2004	Preprocessed data from winter 2004 archived	T6.2	3
M6.5	30.11.2005	Preprocessed data from winter 2005 archived	T6.2	3
M6.7	31.03.2006	Deliverable D14: Handbook on design of protection dams	T6.4	2
M6.8	31.03.2006	Deliv. D15: User manuals for advanced models	T6.5	3/1

Table 1.2: List of deliverables.

Deliverable No.	Responsible partner	Deliverable title	Due date (month)	Nature	Dissemination level
1	SGUL, DAMTP	Web site and meta-data archive	6	Da	PU/CO
2	NGI	Management progress report #1	7	Re	CO
3	NGI	1st Annual scientific report and related materials	14	Re	CO
4	NGI	Management progress report #2	19	Re	CO
5	NGI	Mid-term review meeting	25	Meeting	
6	ETNA, DAMTP	Summary publication on sensor design and data analysis techniques	26	Re	RE
7	NGI	2nd Annual scientific report and related materials	26	Re	CO
8	DIIA	Updated report on European avalanche test sites	26	Re	PU
9	NGI	Management progress report #3	31	Re	CO
10	DIIA	Documentation of instrumentation scheme and installation work at the selected sites	35	Re	PU
11	SGUL	Summary publication on results from small and large-scale experiments	42	Re, Da	PU
12	SGUL	Summary publication on avalanche / dam interaction measurements	42	Re, Da	PU
13	IMOR, ETNA, NGI, DIIA, SGUL, DAMTP	Models of specific processes in avalanche flow and sample modules for inclusion in numerical codes	42	Re, Th, De	PU/CO
14	IMOR	Handbook on deflection and catching dam design	42	Re	PU
15	IMOR, NGI, ETNA, DIIA, SGUL, DAMTP	User manuals for advanced models in avalanche hazard mapping	44	Re	PU
16	NGI	3rd Annual scientific report and related materials	38	Re	CO
17	NGI	Technology Implementation Plan	42	Re	CO
18	DIIA, ETNA	European Summer University 2004 on avalanche hazard mapping	24	O	PU
19	NGI	Final report and related materials	46	O	PU

related to D11 and D12, analysing all data from Ryggfonn of sufficient quality, is in print at Cold Regions Science and Technology. It is expected that work based on results from SATSIE will lead to further publications.

M4.12: The summary report on the measurements in Ryggfonn during the winter 2006 is available from the attached Compact Disc.

M5.2: Publications relating to ETNA's model MN2L were included in earlier Annual Reports. The latest draft versions of NGI reports describing the flow-regime changing model and a general framework for taking into account strongly curved topography in depth-averaged gravity mass flow models are contained on the enclosed Compact Disc. Work on this model is ongoing; scientific papers will be published once the numerical implementation is completed.

M5.3: A publication on the validation of ETNA's model MN2L was included in the preceding Annual Report. NGI's D2FRAM will be validated when its implementation has been completed.

M5.4: Deliverable D13 (new models) has been completed with regard to MN2L, but not yet with re-

gard to NGI's flow-regime changing model. MN2L is being distributed to qualifying avalanche practitioners in France.

M6.4, M6.5: Archiving of the experimental data from SATSIE has been completed, including the winter 2006.

M6.7: Deliverable D14 (Handbook on the design of deflecting and catching dams) could not be completed within the project period. A draft version in an advanced stage has been written and is attached to this report to document the present stage of the work. The handbook will be finalised when consensus has been reached within the handbook writing team on all major issues.

M6.8: Deliverable D15 (User manuals for new avalanche models) has been completed for ETNA's model MN2L (in French and English). The manual for NGI's new model can be written only after the model has been completely implemented and sufficiently validated.

Status of deliverables due by the end of the project:

D6, D8, D10, D11, D12: These reports are delivered as part of this Final Report. See above for more specific information.
A scientific paper analysing all data from Ryggfonn of sufficient quality is in print with Cold Regions Science and Technology. The final version is available on the CD. It is expected that work based on results from SATSIE will lead to further publications.

D13 Models of specific processes in avalanche flow and sample modules for inclusion in numerical codes: Completed for ETNA's new model (MN2L), which has been introduced to practitioners in France. Delayed for NGI's new flow-regime changing model; will be completed as soon as possible.

D14 Handbook on deflection and catching dam design: In advanced draft stage, see above for more specific information.

D15 User manuals for new avalanche models: Completed for ETNA's new model (MN2L), which has been introduced to practitioners in France. Delayed for NGI's new flow-regime changing model; will be completed as soon as possible.

D17 Technology Implementation Plan: Completed and submitted to Scientific Officer. The list of results and the correspodning summaries are reproduced in Section 4. (pages 49 ff.).

D19 The present document.

1.4 Deviations from the work plan or/and time schedule

Below we list the deviations from the work plan (in its revised form with adjustments for the project prolongation) and list of milestones and deliverables:

Deliverables D8 and D10: Drafts of the documents are finished, delays were incurred only with certain last-minute adjustments and the reviewing process. There is no impact on the project as no other work or deliverables depend on them.

M3.9: Investigation of the malfunctioning FMCW radars and their repair were not yet completed at the end of the reporting period. Reinstallation of the radars has been scheduled for November.

Model development: Development of NGI's new models describing flow-regime changes has progressed more slowly than anticipated. Further delays would negatively affect deliverables D13 and D15 as well as the planned advanced course on snow avalanche modelling. Therefore, NGI has allocated additional funding (from sources outside the project SATSIE) to further this work.

1.5 Coordination and communication

No particular difficulties have been encountered in communicating among the project members. The coordinator wishes to thank all partners for their dedicated effort and their friendship that has made working in this project such a memorable experience. Thanks are equally due to Denis Peter, Scientific Officer, for his interest in the progress of our work and the many valuable suggestions he made.

Unfortunately, communication with the Financial Department of DG XII was difficult in that queries by the coordinator were answered with long delays and our biannual reports were repeatedly lost for extended periods. As this was not reported back to the coordinator for several months, our cost statements were not processed in due time and no money was transferred—a circumstance that brought at least one consortium partner into difficulties.

Table 1.3: Gantt diagram, updated per 30/09/2005.

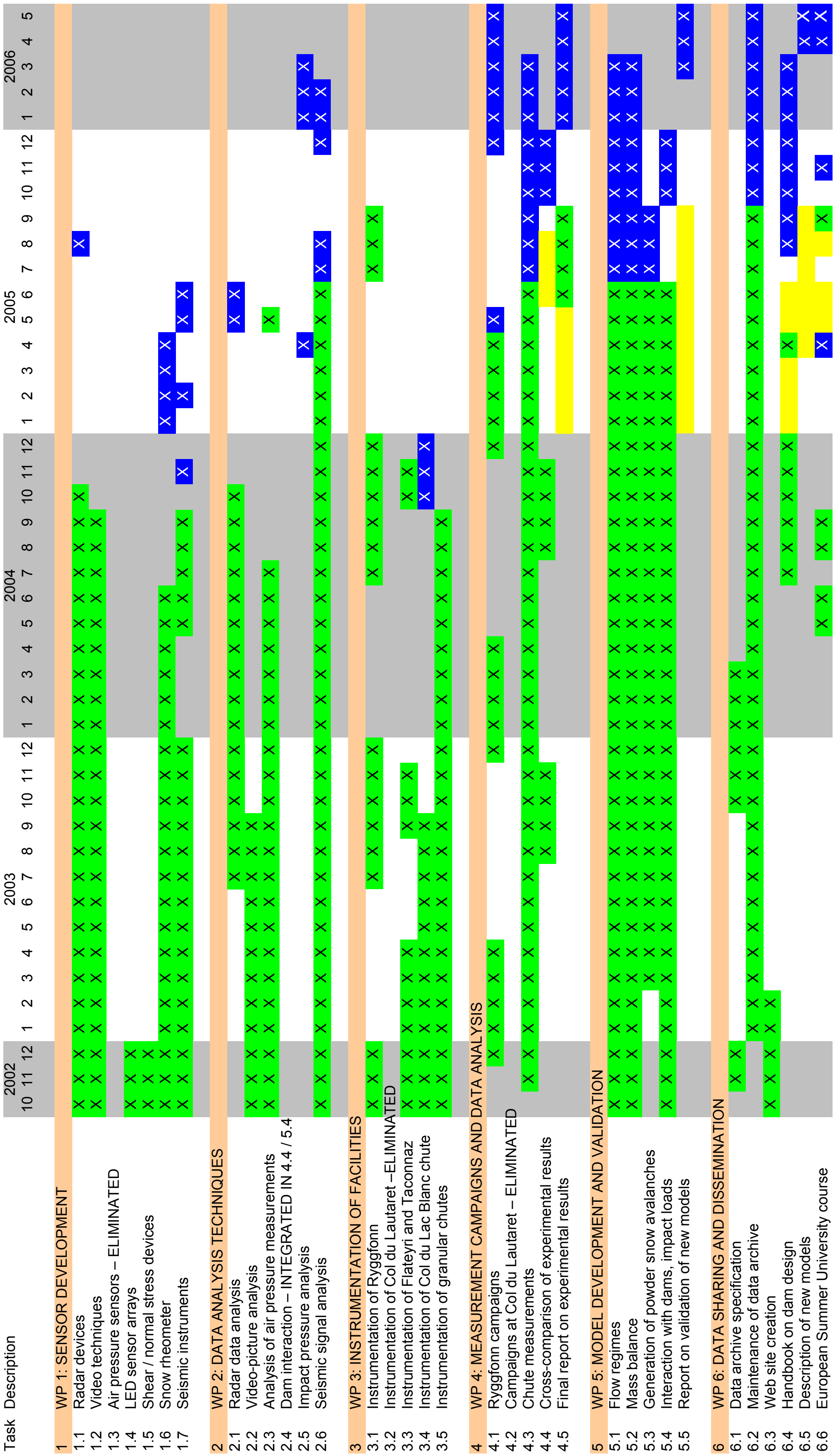

Table 1.4: WPM table for the fourth year, 01/10/2005–31/05/2006.

SATSIE: Resource use (personnel / O.costsReporting period: October 1, 2005 – May 31, 2006

PM: Personnel months O. costs: O.costs in Euro

Partner		1	NGI	2	IMOR	3	DAMTP	4	SGUL	5	AIATR	6	INW	7	ETNA	8	DIIA	9	DGG	Tot.pers.	Total
		PM	O.costs	PM	O.costs	PM	O.costs	PM	O.costs	PM	O.costs	PM	O.costs	PM	O.costs	PM	O.costs	PM	O.costs	months	O.costs
Coor-	*planned*	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.10**	**0.00**
dination	*used*	2.18	5807.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.18**	**5807.58**
	Diff.	0.08	5807.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.08**	***5807.58***
WP 1	*planned*	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50	639.00	0.00	0.00	0.00	0.00	**3.20**	**639.00**
	used	1.81	3096.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50	639.00	0.00	0.00	0.00	0.00	**4.31**	**3735.75**
	Diff.	1.11	3096.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.11**	**3096.75**
WP 2	*planned*	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.00**	**0.00**
	used	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1220.14	**0.00**	**1220.14**
	Diff.	0.00	0.00	0.00	0.00	-2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1220.14	**-2.00**	**1220.14**
WP 3	*planned*	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**1.80**	**0.00**
	used	0.82	4629.29	0.25	929.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.40	0.00	0.00	2747.00	**2.47**	**8305.29**
	Diff.	0.02	4629.29	0.25	929.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	2747.00	**0.67**	**8305.29**
WP 4	*planned*	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	3000.00	0.00	0.00	7.66	0.00	0.00	0.00	0.00	0.00	**11.66**	**3000.00**
	used	2.71	7569.14	0.00	0.00	0.00	0.00	1.90	61.51	1.30	3249.81	0.00	0.00	7.66	0.00	0.00	0.00	0.00	1495.00	**13.57**	**12375.46**
	Diff.	0.71	7569.14	0.00	0.00	0.00	0.00	1.90	61.51	-0.70	249.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1495.00	**1.91**	**9375.46**
WP 5	*planned*	0.80	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	3.30	0.00
	used	1.18	2525.64	1.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	4.68	2525.64
	Diff.	0.38	2525.64	-1.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.38	2525.64
WP 6	*planned*	1.50	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.25**	**0.00**
	used	0.68	853.89	1.75	2236.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.53**	**3089.89**
	Diff.	-0.82	853.89	1.00	2236.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.28**	**3089.89**
Total	*planned*	**7.90**	**0.00**	**2.75**	**0.00**	**2.00**	**0.00**	**0.00**	**0.00**	**2.00**	**3000.00**	**0.00**	**0.00**	**11.66**	**639.00**	**0.00**	**0.00**	**0.00**	**0.00**	**26.31**	**3639.00**
	used	**9.38**	**24482.29**	**3.00**	**3165.00**	**2.00**	**0.00**	**2.00**	**61.51**	**1.30**	**3249.81**	**0.00**	**0.00**	**11.66**	**639.00**	**0.40**	**0.00**	**0.00**	**5462.14**	**29.74**	**37059.75**
	Diff.	**1.48**	**24482.29**	**0.25**	**3165.00**	**0.00**	**0.00**	**2.00**	**61.51**	**-0.70**	**249.81**	**0.00**	**0.00**	**0.00**	**0.00**	**-0.40**	**0.00**	**0.00**	**5462.14**	**2.63**	**33420.75**

Chapter 2

Executive Summary 01/10/2005–31/05/2006

Contract no.	EVG1–CT2002–000590	Reporting period	01/10/2005 – 31/05/2006
Title	SATSIE – Avalanche Studies and Model Validation in Europe		

Main objectives of reporting period:

- Test new FMCW radar system at Ryggfonn and improved snow rheometer at Col du Lac Blanc.
- Measurement campaigns at Ryggfonn, several series of chute experiments at Col du Lac Blanc and in Pavia.
- Theoretical studies and modelling of flow-regime transitions, entrainment, powder-snow avalanche flow and seismic signals generated by avalanches.
- Continue studies of shock formation in avalanche–dam interactions.
- Complete handbook on dam design. Preparations for advanced course on avalanche modelling (European Summer University 2006).

Scientific achievements:

- Avalanche activity was very low in Ryggfonn throughout the winter 2006. An artificially released avalanche did not reach the instrumented section of the path.
- The sensitivity of the repaired FMCW radar systems at Ryggfonn deteriorated again. The reason for this is being investigated.
- Chute experiments at Col du Lac Blanc and Pavia refined earlier experiments and corroborated their findings (velocity profiles, entrainment rates and mechanisms, etc.). New series of chute experiments with granular matter and snow on avalanche–obstacle interaction confirm shock theory at high Froude numbers and may show deviations from theory in snow flows at Froude numbers around 3.
- ETNA's new avalanche model MN2L introduced to French practitioners. Progress was made in extending the NIS model to describe flow-regime transitions (D2FRAM), but the work could not yet be completed.
- Intense work on the handbook of dam design produced a draft version, but publication has to be held back until all remaining open questions addressed by the handbook have been settled.

Socio-economic relevance and policy implications:

After the successful European Summer University 2004, dissemination of project results to the interested public (government agencies, avalanche practitioners) will largely occur through the deliverables due at the end of the prolonged project in mid 2006. An exception is the new French avalanche model MN2L, which is already being distributed to the Service Réstitution Terrains en Montagne in France.

Work during the final phase of SATSIE was strongly directed towards synthesis of the new results and application to products with socio-economic relevance, i. e., improved models for avalanche hazard mapping, a practical handbook for improved dam design, and dissemination of our results. Preparations for an advanced European Summer University course on the use of the new models in avalanche hazard mapping are under way.

It may be several years until the results of SATSIE will fully bear fruit in practical work because the use of new monitoring instruments, hazard mapping techniques and dam design criteria percolates only gradually among the agencies in charge of avalanche hazard management. Some products of SATSIE are ready for use, e. g. the improved Doppler radar for monitoring avalanche paths, ETNA's avalanche flow model MN2L and the new data analysis techniques. There is a range of products that need a little more development time to become ready for practical applications. Chief among them are the FMCW profiling radar, NGI's flow-regime changing avalanche model (D2FRAM), and the comprehensive handbook on dam design. The SATSIE partners are committed to carrying the necessary developments to the end even after the conclusion of SATSIE.

Keywords:

Snow avalanches, mitigation, hazard mapping, avalanche monitoring, handbook of dam design, radar, full-scale experiments, chute experiments, flow regimes, entrainment, shock formation, powder-snow avalanches.

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Planned publications

After the conclusion of SATSIE, a substantial number of scientific publications will be completed and submitted to refereed international journals. In addition, several reports as well as various contributions to conference proceedings are expected to flow directly from project work. The major works will be a comprehensive review of experimental results in snow avalanche research and their implications (based on Deliverable D11), several papers on the results from Ryggfonn and the chute experiments with respect to flow regimes and entrainment, and on the modelling of flow regime changes in D2FRAM. Another major publication, directed towards practical use by engineers, will be the handbook on dam design (Deliverable D14).

Chapter 3

Scientific Progress Report 01/10/2005–31/05/2006

3.1 WP 1 – Sensor development

3.1.1 Objectives for the reporting period

Task 1.1 – Radar techniques: Monitor the performance of the FMCW radar systems installed in Ryggfonn.

Task 1.6 – Snow rheometer: Test the improved instrument during the winter at Col du Lac Blanc.

Task 1.7 – Seismic sensors: Monitor the performance of the modified setup of the data acquisition system during the winter from Barcelona.

3.1.2 Scientific achievements during the reporting period

Task 1.1: Radar techniques

Description The FMCW (Frequency Modulated Continuous Wave) snow profiling radars are placed in caverns looking upwards through a protecting plastic cove into the snow masses passing above down the avalanche track. There are in total four radars placed out in two pairs, one pair at the foot of the dam, the second pair 100 meter uphill. The purpose with this configuration is to estimate the avalanche speed as a function of height above ground by time-correlating the measurements from the two radars in one pair.

Main technical characteristics:

- Frequency range: 2.6–4.6 GHz.
- Modulation: linear up and down frequency sweep.
- Measurement speed: 200 measurements per second.
- Transmitter power: approximately 1 W.
- Antenna configuration: separate transmit and receive antennas, each is an 8 element group antenna using wide-band horn elements.

Log *The winter 2003/2004.* In our work finishing the radars for installation in the fall of 2003 the printed circuit board (PCB) manufacture delivered circuit boards with so much contamination that they

could not be soldered. This setback caused a delay that stopped us from installing the radars since the radar caverns were covered by avalanche deposits early in December.

The winter 2004/2005. All four radars were installed in the late fall of 2004. On the radar closest to the dam the power supply to the microwave amplifier failed later on. On a second radar abnormal behaviour of the power supply was observed. This failure of the power supplies might have been caused by a design weakness which left the radars transmitting continuously for long periods.

For those radars with working power supplies we observed a steady decrease in received power from one week to the next. At the time of the first avalanche late in December the avalanche could hardly be detected. After removal of the radars in the summer of 2005 signs of corrosion on the antenna connectors were observed. Measurements indicated this corrosion was the cause of the falling received power observed after installation. To prevent corrosion the connectors were varnished.

Some other weaknesses concerning variation in output power during the frequency sweep were also observed. To sort out these issues, the developers from NGI and the Technical University of Graz met in Graz. During this stay the problem was isolated to be an inductor resonance, and immediately fixed. In addition local oscillator leakage into the radio frequency port on the receiving mixer was identified as an unwanted signal component. It was decided not to take any actions since the impact of this leakage was evaluated to be insignificant.

The winter 2005/2006. All four radars were installed in late November 2005. In the weeks after installation the same decrease in received power as observed last winter could be seen. No obvious cause of this power decrease was apparent, but we suspected the antenna laminate might absorb humidity. Since there had only been one small avalanche so far into the winter it was possible to dig up the radars and replace the antennas with a new type of wide-band horn antennas without any glass fibre laminate. This was done in early January. During this operation one antenna unit was damaged, so only three radars were installed. Immediately after installation the received power was very good, but in the next weeks even with these new antennas the received power started to decrease again. When avalanches finally occurred later in the winter, the received power level was too small to even detect them.

Achieved results and discussion. Despite best efforts throughout the entire project, the FMCW snow profiling radars could not be brought to function correctly during an entire winter in Ryggfonn. Although the slow decrease observed in received power makes us suspect humidity is the main source for radar malfunctioning, we are at this time not certain. NGI has therefore decided to thoroughly test all aspects of the radars this summer and fall, and thereafter take the necessary actions to achieve a satisfactory performance in the coming winter. This activity will be paid by NGI. We still believe the FMCW snow profiling radars have the potential of producing measurement results of significant value.

Task 1.6: Snow rheometer:

An inflatable membrane was successfully installed inside the large rheometer. But various tests at Col du Lac Blanc in the course of the winter 2005/2006 showed that this modification did not lead to stable shearing conditions. We started the tests by imposing an initial pressure in the inflatable membrane in order to force the snow to stay in contact with the inner cylinder of the rheometer, then we waited until the snow stopped deforming under this pressure. Immediately after the rheometer started rotating, the snow started again to be compressed and the pressure inside the membrane diminished significantly. The tests were not conclusive in that the system did not produce meaningful results yet, but there is still reason to hope that further modifications may succeed. The next step will be the development of a system to control the pressure inside the membrane during the test.

Figure 3.1: The annular snow rheometer during the tests at Col du Lac Blanc, winter 2005/2006. The snow to be tested is filled into the annular space between the two concentric drums. The inflatable black membrane lining the outer drum is clearly visible.

Task 1.7: Adaptation of seismic instrumentation to the conditions encountered in avalanche paths

The technical improvements performed in the seismic Data Acquisition System (DAS) REFTEK 130 prior to the winter season 2005–2006 proved to be successful. The data logger has not experienced any technical problem. It has recorded two small-sized events. The used configuration proved to be robust. It has been possible to connect and command the logger through regular modem connection.

3.1.3 Suggestions for future development work

With the sensors available before SATSIE and those developed in the course of the project, a wide variety of instruments for measuring diverse aspects of avalanche flow can be used in full-scale test sites or in smaller settings like chutes. Some of the sensors developed in WP 1 require additional work to become routinely usable:

- A final effort needs to be made to solve the problem of the deteriorating receive signals in the FMCW radar. Only then can its performance in snow measurements be conclusively assessed. We are still convinced that this instrument design holds high promise.

- Similar problems with humidity have plagued the air pressure sensors for powder snow avalanches. An improved design has been proposed, but financing needs to be found.

- With moderate modifications and an additional winter for refining the experimental procedures, the feasibility of rheometric measurements in rapidly sheared snow will be clarified.
- In addition, laser scanning has been shown to be a very promising method for determining the overall mass balance of avalanche events. The range of presently available instruments is stretched to the limit in the two large-scale test sites in Europe, Ryggfonn and Vallée de la Sionne. Technological improvements may be expected in the near future, but are far beyond the scope of avalanche research institutions.

Chief among the quantities that should be measured but could not is the density. Pressure measurements have given indirect information, but direct measurements are needed to reduce the uncertainties. Capacitance probes are at present arguably the most promising candidate (Dent et al., 1998), and an effort should be made to test them more extensively and deploy them in larger numbers in the experimental facilities.

3.2 WP 2 – Data analysis techniques

3.2.1 Objectives for the reporting period

Task 2.1 – Data-analysis techniques for radars: Completion and testing of the programs for Doppler and FMCW radars.

Task 2.3 – Air pressure sensor analysis: Propose improvements to the air-pressure sensors at Vallée de la Sionne.

Task 2.5 – Impact pressure analysis: Improvement of the analysis technique proposed by (Schaer and Issler, 2001) if and when SLF makes high-frequency measurements from Vallée de la Sionne available.

Task 2.6 – Seismic signal analysis techniques: Develop methods to determine avalanche seismic energy dissipated along the track and to estimate the evolution of friction coefficients along the Ryggfonn avalanche path.

3.2.2 Scientific achievements during the reporting period

Task 2.1 – Data-analysis techniques for radars: The data evaluation is based on the velocity (Doppler frequency) spectra measured by the pulsed Doppler radar. Those spectra were calculated by the radar with a spatial resolution of typically 25–50 m and a time resolution of about 100 ms. From all the spectra of one single range-gate during a whole measurement a time-series can be calculated by using the velocity with the highest intensity peak in the spectrum.

After that calculation we have time-series of the avalanche's velocity for each range-gate and those time-series are the base of the next evaluation step: Determination of the front position and the front velocity. For this evaluation the three-dimensional profile of the avalanche path is necessary as additional information beside the measured spectra.

Description of the calculation process :

1. Determination of the time when the avalanche enters a range gate. This can be read from the time series: If the avalanche is already fully developed there is a jump from 0 to nearly the avalanche's maximum velocity in the time series at that time stamp.
2. Determination of the velocity at the entry point (also from the time-series) and performing a geometrical correction of this velocity using the profile (the radar measures only the radial velocity and not the actual ground velocity which may be higher depending on the angle between the antenna beam and the avalanche path).
3. Calculation of the path length the avalanche covers until the next measurement time stamp by using the profile and the velocity from step 2. If there are changes in the direction of the path during this time period the calculation is split and the velocity is corrected accordingly for each path segment separately.
4. Using the velocity at the next time stamp, step 3 is repeated until reaching the time stamp when the avalanche enters the next lower range-gate.
5. Typically at the end of this calculation the avalanche front position is not at the border-line between the range gates involved. Therefore the used velocities must be adapted and the process repeated.
6. Steps 1–5 are repeated for the next lower range gate until the avalanche stops.

7. The uppermost range gate where the avalanche starts must be treated differently: The calculation of the position starts at the lower range gate border and moves upwards and back in time until the release of the avalanche.

Task 2.2 – Video analysis: This was previously completed.

Task 2.3 – Air pressure sensors: The air pressure transducers were sent off to the manufacture for failure analysis. The problem was identified as overpressure. We believe that this was due to the build up of ice in the transducers. This was because the heating elements were on the sensor outlets and set up a positive temperature gradient from the outlets to the transducers. This temperature gradient resulted in a gradient in the saturated vapour pressure and hence a flux of water vapour towards the transducer. Over several months this flux caused the accumulation of sufficient ice to break the sensor. An analysis of this was written and a new proposal for an improved sensor submitted. This is included in Deliverable D6.

Task 2.5 – Impact pressure analysis: This task was abandoned due to lack of access to suitable data. The allocated time was previously transferred to other tasks.

Task 2.6 – Seismic signal analysis techniques:

- Determination of the front speed of the avalanche released on 2005-04-16 using seismic methods.
- Determination of seismic characteristics of the Ryggfonn soil: Phase velocity for superficial waves and attenuation factor of seismic waves with distance
- Determination of the energy transmitted into the ground by the 2005-04-16 artificially released avalanche in Ryggfonn using the developed techniques. The obtained results coincide with the mass and size classification proposed by NGI. These results were presented in April 2006, at the EGU General Assembly (Vienna).

Task 2.7 – Correlation Methods: This was previously completed.

Figure 3.2: Deflector wall destroyed by the large Taconnaz avalanche in April 2006. The sensor was torn off before data could be transmitted to the logger.

3.3 WP 3 – Instrumentation of selected facilities

3.3.1 Objectives for the reporting period

This task was essentially completed earlier. Revision of the FMCW radars and the snow rheometer required some (re-)installation work at Ryggfonn and at Col du Lac Blanc.

3.3.2 Achievements during the reporting period

Task 3.1 – Full-scale avalanche test site Ryggfonn (Norway): The FMCW radar systems were successfully reinstalled before the beginning of the winter. As soon as possible after the winter, DGG's seismic equipment was repatriated to Barcelona.

Task 3.2 – Protection dam system in Taconnaz (France): Before the beginning of the winter, minimal maintenance work was performeed on the pressure sensors. A large wet-snow avalanche destroyed the sensor system in April; the remains were collected for later analysis.

Task 3.3 – Protection dam system in Flateyri (Iceland): Only standard maintenance work on the radar system was performed.

Task 3.4 – Snow chute at Col du Lac Blanc: The snow rheometer was transported to Col du Lac Blanc.

Report on installation work: Deliverable D10 was finalised.

3.3.3 Suggestions for future work on the facilities

Coordinated planning of experimental facilities: In the long run, maintenance and use of a full-scale avalanche test site is too costly for a single institution in the field of natural hazards research. Joint financing, development and use of the existing facilities at the European level could solve this problem and at the same time improve the scientific return on the investments. The SATSIE consortium, extended by SLF (Switzerland) could take the lead in exploring various scenarios and elaborating a proposal for an appropriate organisational structure.

Long-term maintenance of the Ryggfonn site: If Ryggfonn is to be used in the future as a full-scale test site with similar objectives as in SATSIE, the artificial release system, the cabling and the data acquisition system need to be replaced as soon as possible. The reliability of the system is mainly limited by the aging cables. The data acquisition system is at its limits with regard to the number of channels and the data transfer rates. The old remotely controlled release system iws no longer operational; a new system needs to be installed as soon as feasible.

Priorities for additional instrumentation at Ryggfonn: *Initial conditions, global mass balance:* A laser-scanning system for acquiring snow depth distributions before and after an avalanche event would provide the initial conditions that had to be estimated crudely so far. *Additional FMCW radar pair near upper mast:* This would allow measurement of flow depths and velocity profiles that can be correlated with the pressure measurements at the same location, allowing more conclusive interpretation of either data set. *Capacitance sensors at concrete structure or upper mast:* Direct measurements of density at various heights in the flow are important for understanding the layering of avalanches and validating advanced dynamical models.

Additional equipment for chutes: In order to better understand the influence of particle properties on the rheology of granular and snow flows, the chutes in Pavia and at Col du Lac Blanc should be equipped with equivalent instruments and use essentially the same protocols so that measurements can be directly compared.

New instrumentation for the Col du Lautaret site: ETNA is planning to re-equip their small full-scale site in the Savoyan Alps with equipment similar to that used at the Col du Lac Blanc chute in order to study the scaling behaviour of the effects observed at small scale.

3.4 WP 4 – Measurement campaigns

3.4.1 Objectives for the reporting period

Task 4.1 – Full-scale measurements at Ryggfonn: Conduct measurement campaigns as in the previous winters, with as many sensors as possible. Manual survey of deposits.

Task 4.3 – Chute measurements: At the Col du Lac Blanc snow chute, perform further focused measurements of the bottom shear layer and infer properties of snow-particle aggregates. Complement chute experiments with rheometer measurements. At the granular chutes in Pavia, perform experiments with quasi-steady flow and study impact on various types of obstacles. Extend erosion experiments to other materials in a new chute.

Task 4.4 – Analysis and cross-comparison of results at different sites: Compare avalanche structure, velocity profiles, over-all force balance and entrainment/deposition rates between full-scale events and chute flows. Comparison between interactions of avalanches with deflecting dams in nature and in the laboratory if data becomes available.

Task 4.5 – Elaboration of final reports on experimental results: Complete the documentation of all performed experiments and full-scale measurements in two reports on avalanche processes and on avalanche–dam interactions. Submit review article on experimental knowledge of avalanche dynamics.

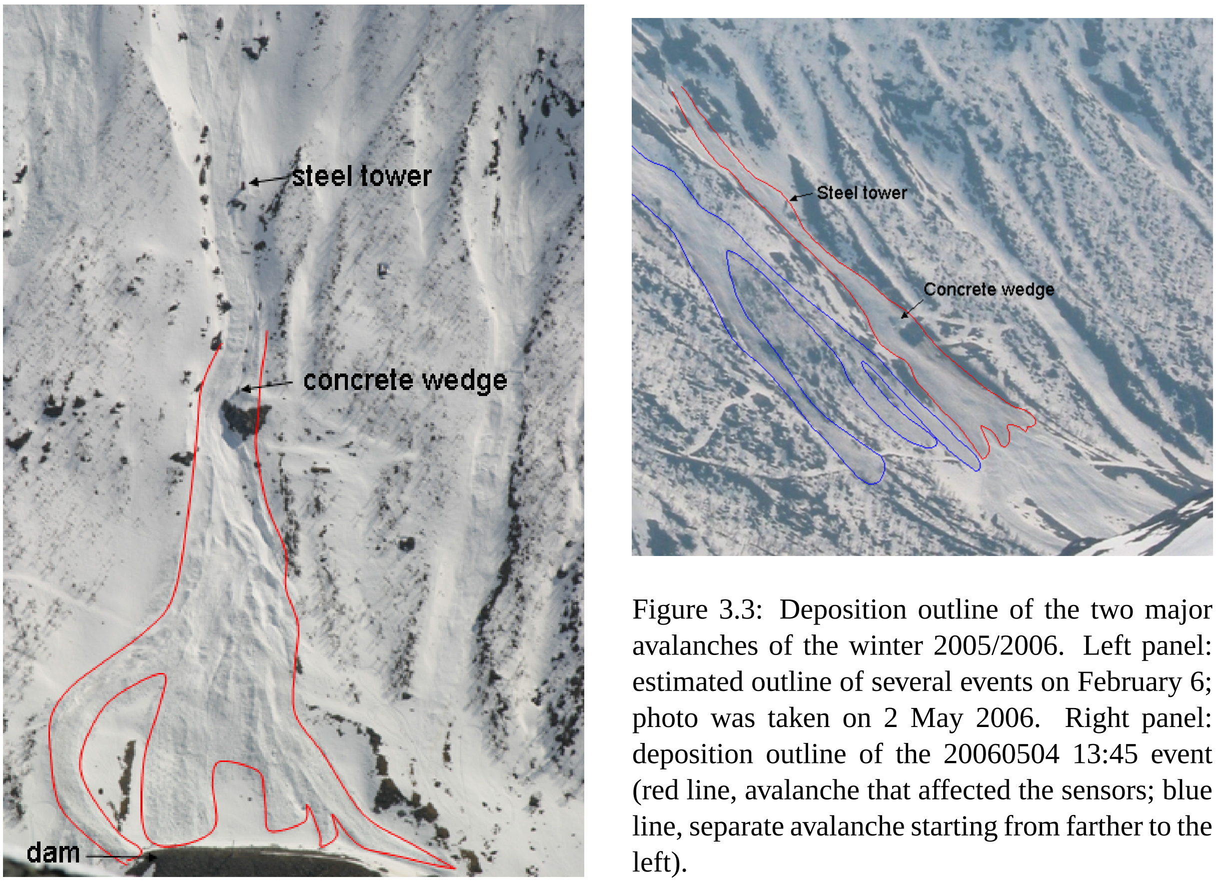

Figure 3.3: Deposition outline of the two major avalanches of the winter 2005/2006. Left panel: estimated outline of several events on February 6; photo was taken on 2 May 2006. Right panel: deposition outline of the 20060504 13:45 event (red line, avalanche that affected the sensors; blue line, separate avalanche starting from farther to the left).

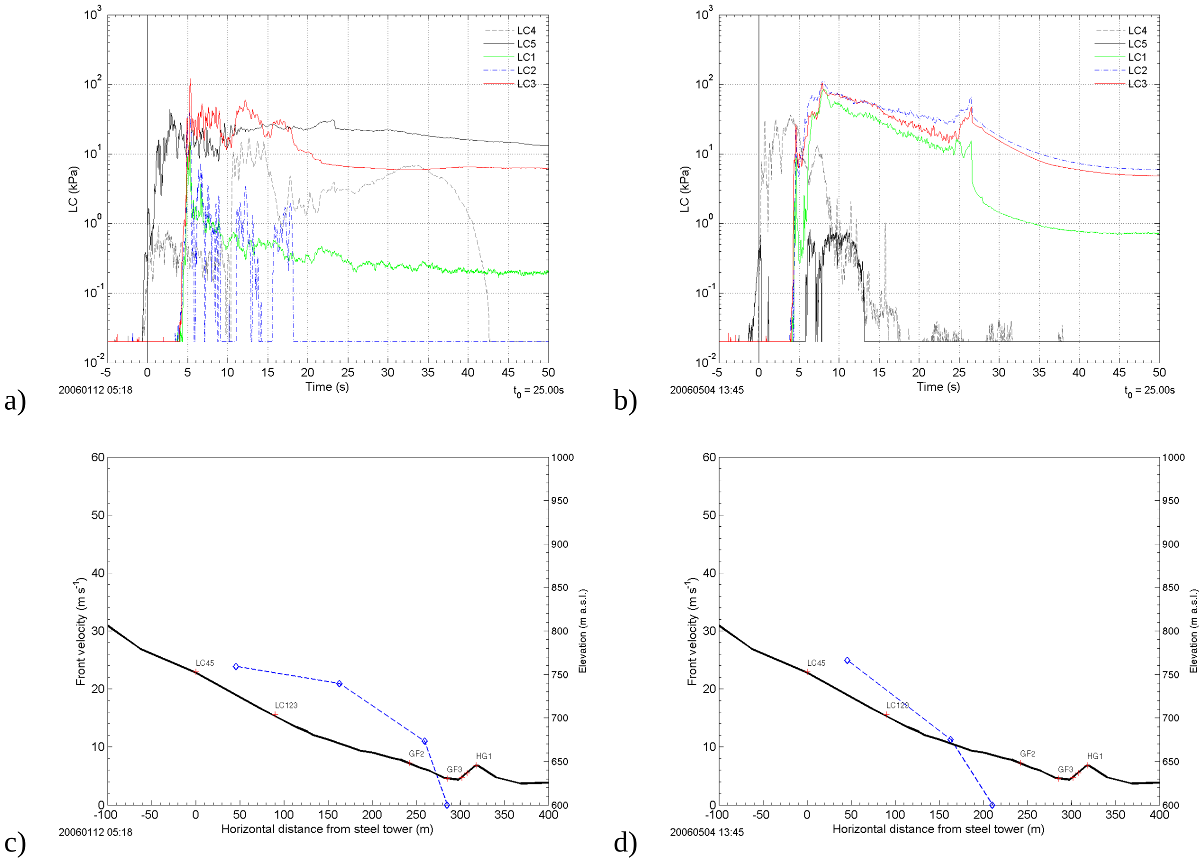

Figure 3.4: (a), (b) Load cell measurements: pressure vs. time (note logarithmic scale; running mean). (c), (d) Estimated front speed based on timing between various sensors. (a) and (c): 20060112 05:18; (b) and (d): 20060504 13:45.

3.4.2 Scientific achievements during the reporting period

Ryggfonn full-scale experiments (NGI)

Events, general remarks. Besides NGI staff, team members from the Department of Geology and Geophysics of the University of Barcelona, and from the Austrian Federal Research and Training Centre for Forests, Natural Hazards and Landscape participated in this task.

Table 3.1: Avalanche classification

Date yyyymmdd hh:mm	Size[1]	Deposit (10^3 m^3)	Classification (ICSI)[2]									Speed (m s^{-1})	
			A	B	C	D	E	F	G	H	J	LC4–LC1[3] 101 m	LC1–LP1[4] 218 m
20051217 15:40	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
20060112 05:18	3	NA	2	1	7	2	2	3	7	1	1	24	–
20060206	2/3	NA	2	1	7	2	2	3	7	1	1	NA	NA
20060206 19:58	3	NA	2	1	7	2	2	3	7	1	1	13	–
20060502 14:10	2	NA	2	3	2	1	2	3	2	1	4	–	–
20060504 13:45	3	NA	1	1	2	2	2	3	2	3	1	25	–

[1] According to Canadian avalanche size classification, cf. (McClung and Schaerer, 1993)
[2] According to International Avalanche Classification ((Avalanche Atlas, on Snow and of the International Association of the Hydrological Sciences, 1981), also in (McClung and Schaerer, 1993))
[3] The estimated average speeds are calculated between the steel tower and the concrete structure,
[4] and between the concrete structure and the foot of the dam, respectively.

Table 3.2: Overview of archived measurements at the Ryggfonn test site, winter 2005/2006.

Date yyyymmdd hh:mm	Geophone (GF)1 2 3 4 5 6 H1	Load cell (LC)4 5 1 2 3	Load plate (LP)1 2	Radar P-DR	 (FMCW) 1 2	Field obs.	Maps
20041217 15:40	X O O O O O O O	X X O O O	O O	–	– –	–	–
20060112 05:18	X X O O O O O O	X X X X X	O O	–	– –	–	–
20060206	– – – – – – –	– – – – –	– –	–	– –	X	–
20060206 19:58	X X O O O O O O	X X X X X	O O	–	– –	(X)	–
20060502 14:10	– – – – – – –	– – – – –	– –	–	– –	X	–
20060504 13:45	X X X X X X X O	X X X X X	O O	–	– –	X	–

Codes: X: data; P: sensor partly buried; B: sensor buried; O: data, but no measured signal (did not reach sensor); –: no data; U: sensor status unknown

The Ryggfonn full-scale avalanche test site has been in operation since 1980. The test site has a vertical drop of about 900 m and a horizontal length of 2100 m. Typical avalanche size ranges from 2 (mass of 100 tons) to 4 (mass of 10,000 tons) according to the Canadian snow avalanche size classification (McClung and Schaerer, 1993); maximum velocities are up to $60\,\mathrm{m\,s^{-1}}$.

Due to the low precipitation during the winter season 2005/2006, only four or five rather small naturally released avalanches reached the sensor area. All of those were damp or wet snow avalanches. In the beginning of May 2006 an artificial avalanche release was attempted. However, only two small slides

Figure 3.5: 20060502 14:10: Snapshots from the track. Left hand side: during the descent of the avalanche. Right hand side: after the event (similar location). Obviously, the avalanche eroded during the descent. Scratch marks remind one of erosion/abrasion due to (saltating) particles. Bottom panels depict close-ups. (Photos by P. Gauer)

could be released, which stopped in the bowl below the release area and did not reach the sensors. Table 3.1 provides an overview and short classification of the different events and Figure 3.3 gives the approximate outline of the two major events. Table 3.2 summaries the conducted measurements for the individual events and gives an estimation of the sensor status during the event.

Results. Despite the rather weak avalanche winter, some measurements and observations could be gained. Figure 3.4 shows the plot of the measured pressure and estimated front velocities of the two major events of the season. Figure 3.5 shows snapshots from the artificially released avalanche on 2nd May. They indicate that also in this rather small avalanche erosion occurred and that abrasion might be a possible mechanism (cf. Gauer and Issler, 2004).

With the intention of determining the mass balance, AIATR did TSL (terrestrial scanning laser) measurements on 1st May, the day before the release. Eight subareas were scanned from one scanner position close to the centre of the dam crown (West-East 409407.984, South-North 6872154.282, altitude 643.823). Lacking post-event data (the released avalanches stopped before becoming visible from the dam crown), the scanning was used to evaluate the depth of the snow cover. Particularly the eastern half of the scanned area shows large negative values (< -4 m; cf. Fig. 3.6)—indicating that the summer terrain (represented by NGI_DTM) has a higher absolute altitude than the snowcover in winter (derived from laser scanner measurements). Low intensity of the reflected beam or perhaps inconsistencies of the NGI_DTM are potential sources for the observed deviations. Scanning the terrain again in summer and/or interpretation of the result by NGI experts will clarify this question.

During the winter season 2005–2006, DGG's seismic equipment recorded the spontaneous avalanche on 6 February and the artificially released one on 1st May 2006. Although the latter avalanche did not reach the lower part of the track, seismic signals from the starting zone were recorded. A representative of DGG (I. Vilajosana) was present at Ryggfonn during the experiment. At the end of this period, the instrumentation deployed by the DGG group at Ryggfonn was returned to Barcelona. Analysis of the data is ongoing.

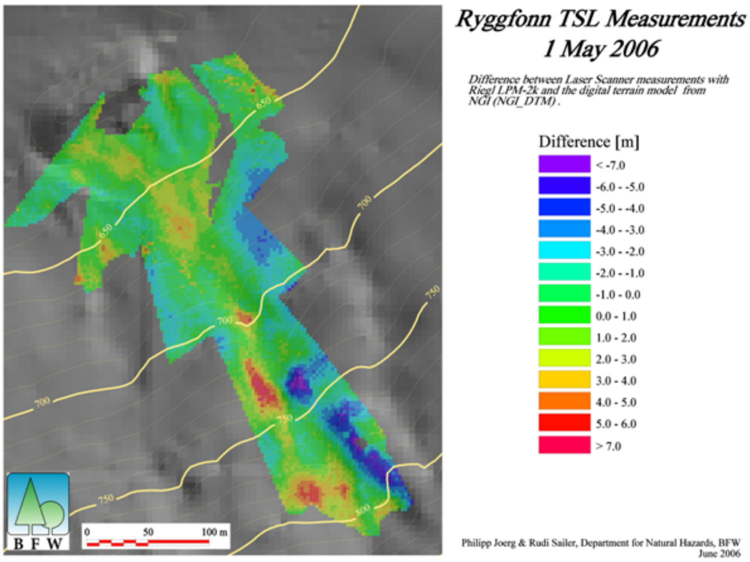

Figure 3.6: Differences (analysed resolution = 2.5 m) between winter surface altitude, derived from laser scanner measurements, and summer surface altitude, represented by NGI_DTM. North is towards the top of the page.

Chute experiments with snow at Col du Lac Blanc

Rheology of flowing snow. During the winter 2005–2006, we carried out six measurement campaigns at Col du Lac Blanc (Alpe d'Huez). We have increased the number of flows in each campaign from 4 flows (last winters) to 10. This allowed us to explore a large range of slope angles and flow depths using the same snow. The used snow was different from one campaign to another; we succeeded to determine how the rheological properties and the friction law are affected by the snow properties.

Fig. 3.7. The Col du Lac Blanc chute during an experiment. Photo: M. Naaim.

Deflection dam measurements. New measurement campaigns were carried out during the winter 2005–2006 at Col du Lac Blanc. These experiments followed the first tests performed during the winter 2004–2005 and investigating steady flows of dense snow down a rough inclined chute and interacting with a deflecting obstacle (Fourrière et al., 2006). These experiments are of considerable practical interest for the design of deflecting dams that are built to defend against large-scale snow avalanches. The deflector, with an upstream vertical face, was located at the end of the 10 m-long and 20 cm-wide snow channel of the Lac Blanc pass. The three main parameters that were varied during the experiments were the channel inclination, the mass flow rate and the deflecting angle of the obstacle. Image processing and analysis allowed us to quantify the influence of both, the upstream incoming Froude number and the deflecting angle, on the maximum run-up reached by the stationary snow flow on the deflector. The data were discussed in comparison with the predictions from simple conversion of kinetic energy to potential energy on the one hand, and from an oblique shock calculation in the framework of shallow-layer theory on the other hand. In the range of the parameters that were tested, the predicted values from the first approach were shown to be in better agreement with the measured values than those from the second approach (Faug et al., 2006). These results were also discussed in comparison with previous small-scale laboratory experiments carried out by Hákonardóttir and Hogg (2005), involving similar geometries with dry granular materials.

Chute experiments with granular materials in Pavia

Flow regimes and regime transitions. Within an avalanche there are a great variety of flow regimes. In the 3rd Annual Report we noted that we had developed a method with the potential for detecting more subtle transitions in flow properties than shifts in the mean or other statistical moments. This has now been published (Keylock, 2006a) and a new version of the algorithm developed for pseudo-periodic data (Keylock, 2006b). The method works by generating surrogate data that preserve the local mean and variance structure but randomises the local Hurst exponent (3.8). Fractional Brownian motion (B) can perhaps be considered as an appropriate test signal owing to its links to Kolmogorov's theory of

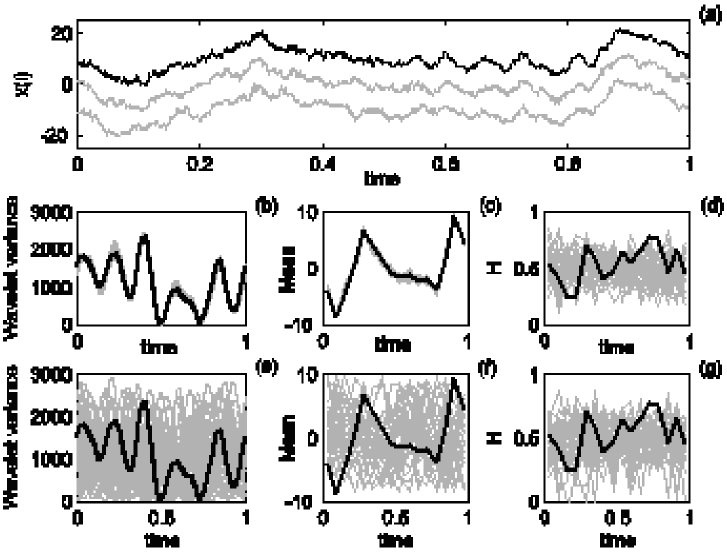

Figure 3.8: Time series and surrogate analysis for fractional Brownian motion with a change in Hurst exponent H from 0.4 to 0.65 at the mid point. The dimensionless time series (black) and two surrogates produced using the algorithm of Keylock (2006) (grey) are shown in the top panel, with vertical displacements to aid visibility. The second row shows properties of the original signal (black) and surrogates (grey) for the method of Keylock (2006) and the third row shows similar information for surrogates generated using the Iterated Amplitude Adjusted Fourier Transform method of Schreiber and Schmitz (1996).

turbulence (Kolmogoroff, 1941). It may be defined as

$$\begin{aligned} B(0) &= 0 \\ \left\langle |B(t) - B(t-\Delta)|^2 \right\rangle &= \sigma^2 \Delta^{2H}, \end{aligned} \tag{3.1}$$

where Δ is some increment, angled braces represent averaging, σ is the standard deviation and H is the Hurst exponent. Kolmogorov defined a structure function of order n as

$$S_n = \left\langle |u(x+\Delta) - u(x)|^n \right\rangle \tag{3.2}$$

and noted that when $S_n(\Delta)$ is plotted against Δ on log-log axes an exponent ζ_n can be obtained with a value of $n/3$. The Hurst exponent may also be defined in terms of structure functions (e. g. Gilmore et al., 2002) as

$$\zeta_n = nH(n). \tag{3.3}$$

Hence, there is an explicit connection between fractional Brownian motion, the Hurst exponent and Kolmogorov's 1941 theory (where H should equal 1/3 for any n). Subsequently, Kolmogorov's theory has been modified with the discovery of intermittency effects (e. g. She and Leveque, 1994). However, it provides a simple model for turbulent flow behaviour as might be expected above and within the avalanche powder cloud, and the Hurst exponent has also been used to describe collisional, granular flow regimes such as are observed in granular chute experiments (Baxter et al., 1993). Significant changes in H may be related to changes in the dynamic properties of the flow (the flow regimes) that cannot be readily derived from an examination of the mean or variance of the velocity field. Such changes can hopefully be detected using methods developed during SATSIE and explained below.

The surrogate-generating method is explained in Fig. 3.9 and differs from the commonly used Iterated Amplitude Adjusted Fourier Transform (IAAFT) method in that it produces surrogates that are "aligned"

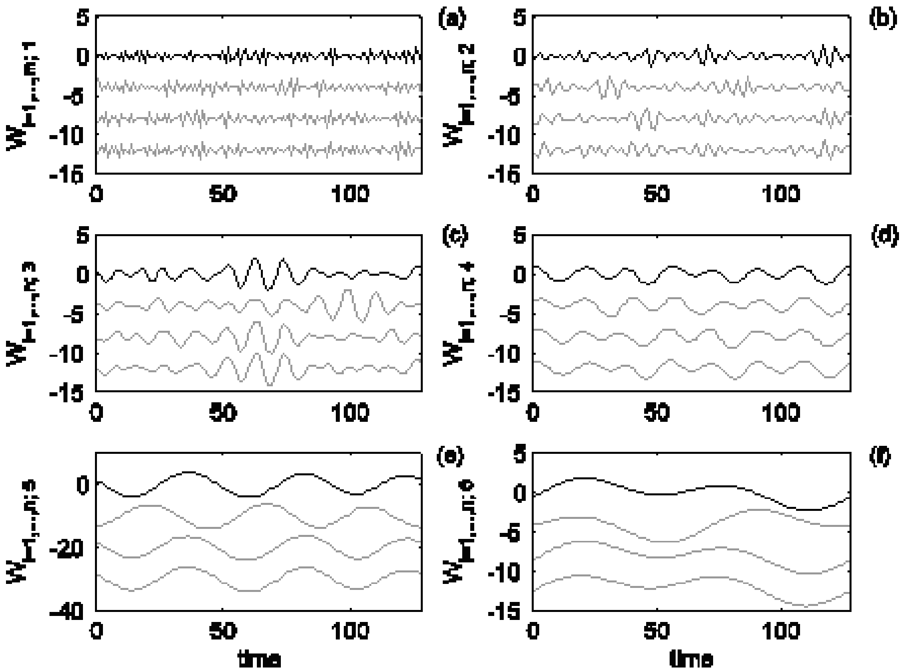

Figure 3.9: Wavelet coefficients $W_{i;j}$ for the first 6 scales j of the time series shown in Fig. 3.10. Values are displaced from one another by 10 in (e) and 4 in all other plots for clarity. The black line shows the wavelet coefficients for the original time-series. The upper grey lines are those that result from applying the IAAFT algorithm to the black line. The middle grey line results from a least-squares matching between the black line and the upper grey line (as well as the mirror image of the upper grey line). The bottom grey line is the final set of coefficients after applying the IAAFT algorithm to the time-series reconstructed from the inverse wavelet transform of the coefficients given by the middle grey line over all wavelet scales.

with the original signal (Fig. 3.10). Application of the Maximal Orthogonal Discrete Wavelet Transform (MODWT) to a time-series of length $n = 2^J$ yields $i = 1, \ldots, n$ wavelet detail coefficients W at $j = 1, \ldots, J$ dyadic scales. Scales $j = 1, \ldots, 6$ for a particular time series are given in Fig. 3.9 as a black line. If we consider each of these sets of wavelet coefficients independently, then we can apply the IAAFT algorithm to each to obtain randomised values that retain the original values and spectral properties (upper grey line in each plot). We then generate the mirror image of this set of values and minimise the distance between the original coefficients and these new sets using an error criterion, retaining either the mirror image or the initial randomised values depending on the minimum. The coefficients are then circularly rotated to the location that minimises the error (middle grey line). After this operation has been performed for all detail coefficients, the original approximation is added back in and the MODWT is inverted to give a surrogate time-series. An iterative procedure identical to the equivalent stages of the IAAFT is then used to recover the original values in the data and maintain the spectral similarity between time-series and surrogates. The bottom grey line shows the coefficients that would result if the final surrogate were to be decomposed using the MODWT. This algorithm is referred to as the WIAAFT method because of the added wavelet-based step.

During the current reporting period a new variant of this algorithm was developed whereby all wavelet coefficients exceeding a specified threshold are frozen in the same locations as they occur in the original data and the remainder are randomised using the IAAFT method before the inverse MODWT is applied as explained above. The improved behaviour of this method for pseudo-periodic data (e. g. perhaps as may occur due to Kelvin-Helmholtz billows at the interface between an avalanche and the surrounding air column or by the development of coherent structures within a granular flow) is shown in Fig. 3.11.

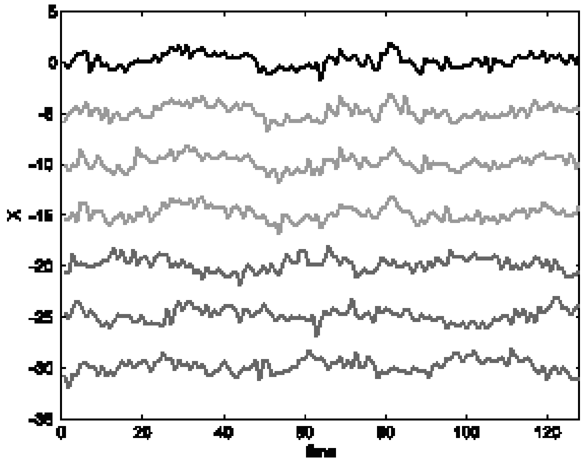

Figure 3.10: The time-series X decomposed in Fig. 3.9 with three WIAAFT surrogates (light grey) and three IAAFT surrogates (dark grey) each displaced from the other by 5 units for clarity. The localisation property of the WIAAFT surrogates is clear.

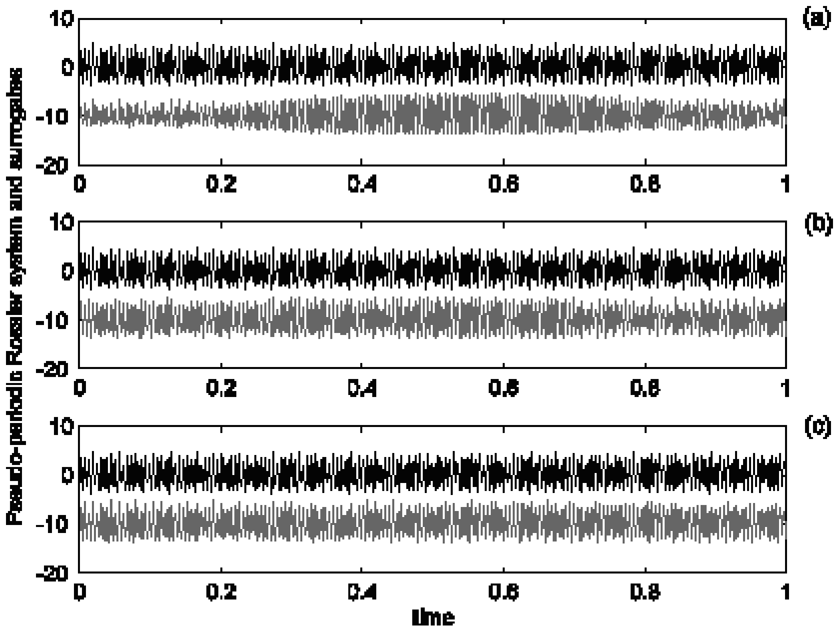

Figure 3.11: Pseudo-periodic time-series generated from the Rössler equations (black) with surrogates shown in grey and displaced by -10 for visibility. The surrogates shown are IAAFT (a), WIAAFT (b), and pinned WIAAFT (c).

The example data provided in this figure are generated using the Rössler set of equations:

$$\begin{aligned} dq/dt &= -(r+s), \\ dr/dt &= q+ar, \\ dr/dt &= 2+t(q-4), \end{aligned} \tag{3.4}$$

where a pseudo-periodic signal was obtained by setting $a = 0.3909$. An attempt was made to test this algorithm by applying it to the granular flow data obtained in the Pavia chutes, where changes in flow behaviour are readily discriminated, meaning that these data would provide a useful test case. However,

unfortunately, the frame speed from these experiments was not sufficiently fast to apply the method because an accurate estimation of the Hurst exponent requires a large data window relative to the length of these time series (4 seconds of data at 125 frames per second $\sim$ 500 frames). Thus, an alternative approach was taken to develop initial tests, which would be more applicable for discriminating processes in the powder component of the flow than the denser layers.

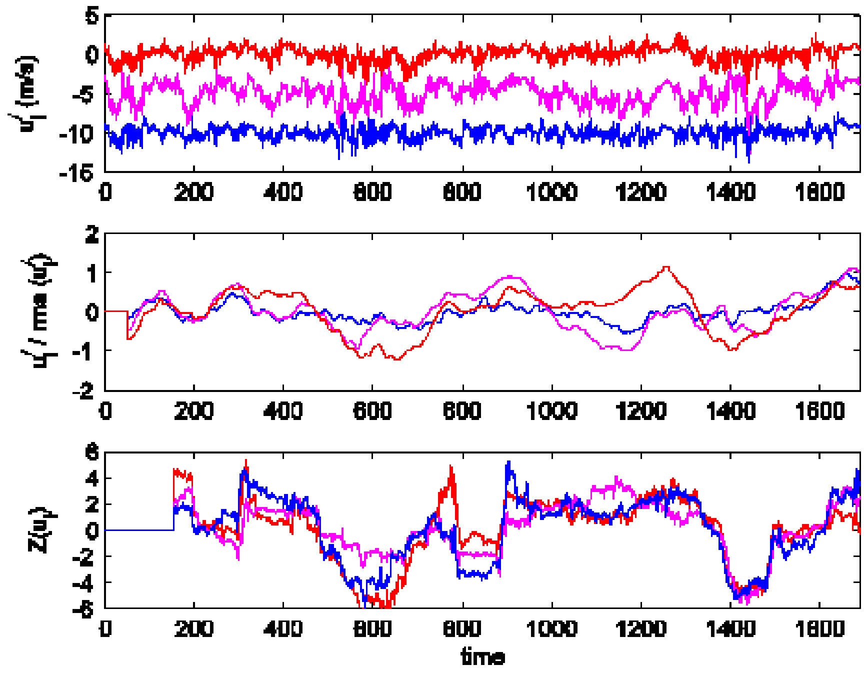

Figure 3.12: Streamwise (u_1 = red), transverse (u_2 = magenta) and vertical (u_3 = blue) velocity components and accompanying Z scores for a statistical test based on surrogates of these data.

Turbulent velocity data were obtained using a sonic anemometer at a frequency of 10 Hz in an environment where there was an occasional alteration of the flow field due to the advection of energetic flow structures past the sensor. These data were supplied courtesy of Prof. Gaby Katul at Duke University and are shown in Fig.3.12. The top panel shows the fluctuating part of the three perpendicular velocity components with each displaced from the other by -5 m/s. The middle panel shows the same data smoothed with a window of length 1024 and normalised by its root-mean square value. The final panel shows the results of undertaking a surrogate-based test for the change in Hurst exponent of these velocity data using a window size of 1024 to estimate the Hurst exponent and the algorithm of Keylock (submitted). Hence, the middle panel equates to the velocity signal resolved at the same scale to which the Hurst exponent is estimated. These results are expressed in terms of a Z score by finding the difference between the local value of H for the data and for the mean of the local values of the surrogates and dividing this by the standard deviation of the local values for the surrogates. Thus, if the magnitude of Z exceeds 2.0 then there is a significant difference at the 5 % level. This is not precisely the case here because there is also an error attached to estimating H. However, our method clearly identifies the times in the record when the velocity signals appear to be much rougher than average (i.e. $t \sim 600$ s and $t \sim 1400$ s) as a reduction in Z (and hence, increase in fractal dimension). These are the times when energetic flow structures impinge on to the flow from above (as determined by the mixing of a tracer gas).

Conclusion: A method has been developed for detecting local changes in roughness in a signal that correspond to process changes. Data limitations have so far restricted testing to turbulent signals. However, use of a higher speed camera on granular flow experiments (e. g. the UK Research Council 4000 frames per second camera) should permit similar analyses in a granular flow regime context. In addition, and at

a larger scale, such a technique has the potential for detecting changes in flow regimes as an avalanche passes a sensor. Following further testing of the method for statistical robustness, we hope to apply this technique to granular flow and avalanche data sets for enhancing our knowledge of flow regime transitions and variability within flow regimes that may relate to the presence of coherent structures.

3.4.3 Suggested future work after SATSIE

Full-scale measurements at Ryggfonn: Measurements should be continued at the test site with the full range of sensors and complemented by manual surveys. If successful, laser scanning for obtaining the global mass balance of events would be an important addition to the presently observed quantities. The major problem will be to obtain sufficient funding for maintenance, measurement campaigns and data analysis.

Chute measurements: The novel statistical data analysis techniques described above suggest that chute experiments, where large amounts of precise data can be obtained under controlled conditions, will be instrumental in detecting flow-regime changes, characterisation of the regimes themselves and understanding the physics controlling them. While studies on dry granular materials are of great value, even more can be gained if they can be compared to similar experiments with different varieties of snow. Also, apparently innocuous differences in experimental setup may be responsible for significant differences in the results, therefore comparison of results from different experiments is most valuable. All these considerations suggest that continued collaboration between the partners who performed chute experiments would provide great benefits in the future.

Cross-comparison of results at different scales: Additional experiments at other scales are highly desirable in order to check whether results obtained at the current laboratory scales of a few metres still hold at larger scales. Large-scale experiments with snow would be particularly useful.

Analysis and cross-comparison of results at different sites: What was said for the chute experiments holds equally well for the full-scale measurements—much can be gained by comparing results from different sites. In Europe, these are Ryggfonn in Norway and Vallée de la Sionne in Switzerland. The future will tell whether such collaboration can be instituted; encouraging beginnings were at least made in SATSIE.

3.5 WP 5 – Model development

3.5.1 Objectives for the reporting period

The goal of the model development work package is to improve the physical basis of currently operational snow avalanche models. The objectives of WP 5 within the reporting period were to finalise the interpretation and reporting of laboratory and full-scale experiments that were carried out in the first phase of the project, continue with the implementation of improved model physics and numerical methods in numerical models, and use these developments as the basis of improved design criteria for avalanche dams in the Satsie handbook, which is being written in Task 6.4.

The objectives of each task within the work package are:

Task 5.1 – Flow regimes: Refine MN2L, ETNA's two-layer model, by implementing velocity profiles from chute experiments. Further work on constitutive equations for 2D depth-integrated avalanche flow that allows for transition from dense to fluidised flow, based on an extension of the Criminale–Ericksen–Filbey rheology, including the implementation of these equations into a numerical model.

Task 5.2 – Snow entrainment and mass balance: Carry on experimental investigations of erosion processes at the new granular chute C in Pavia.

Task 5.3 – Powder snow avalanches: Investigate the dynamics of air flow near the head of a powder snow avalanche using a combination of field observations and theoretical analysis. Also, analyse the internal flow dynamics near the head of powder snow avalanches using experimental results from chute experiments and theoretical analysis based on fluid dynamics for incompressible flow. Develop models and apply them to field data.

Task 5.4 – Interactions with dams, impact loads: Analyse data obtained from natural snow avalanches in Norway, Iceland and France in order to verify theoretical ideas and computational models for avalanche–dam interactions that have been derived during the project and previous research projects. Further analysis of shock dynamics with a focus on avalanche flow over dams. Interpretation of field data, laboratory experiments and existing design guidelines about impact pressures in order to formulate an impact pressure section in the SATSIE dam design handbook, which is being written in Task 6.4.

Task 5.5 – Validation of new models: Compare the design criteria for avalanche dams, which have been formulated for the SATSIE handbook, with available field observations about avalanche run-up on natural terrain obstacles and man-made dams. Test NGI's new model against suitable measurements and observations.

3.5.2 Scientific achievements during the reporting period

Task 5.1 – Flow regimes of snow avalanches: The experiments undertaken at the Col du Lac Blanc chute showed that the velocity profile consists of a thin, highly sheared layer overlaid by the main core of the avalanche, where the shear rate is about one order of magnitude less. These experiments allowed also to determine the constitutive equation of flowing dense snow. These measurements, and evidence from Molecular Dynamics Simulation we have undertaken, highlighted the key role of aggregates in structuring the flow. We implemented the experimental results from the Col Lac Blanc chute in terms of a modified velocity profile and friction law. A publication is under preparation for the Journal of Rheology.

For the flow-regime changing model under development at NGI, two alternative approximate density evolution equations have been formulated, one based on the non-hydrostatic treatment of the momentum

balance in the direction perpendicular to the sliding plane and the other describing relaxation to the instantaneous local equilibrium density. The density dependence of the rheological coefficients is initially specified in terms of fits to the results of numerical simulations of collisions in a sheared 2D granular material and a corresponding 2D kinetic-theory analysis.

The formulation of (general) depth-averaged models on hummocky mountain terrain was considered in detail, without the restrictive assumptions on the curvature that most previous models made. While the general structure of the balance equations known from plane surfaces can be maintained (in particular the conservative formulation), a number of additional terms describe effects due to centrifugal forces. At each time step and for each mesh node, several factors depending on the local geometry and the flow depth need to be evaluated. As this is a critical point for the efficiency of a numerical code, care was taken to devise a calculational procedure that reduces this task to evaluating relatively simple polynomials.

Due to prolonged illness of one participant in this task, the numerical implementation of the new model did not progress and will be pursued after the end of SATSIE. Accordingly, the validation of this model (Task 5.5) and the writing of user manuals (Task 6.5) had to be deferred for this model. – Work at NGI has been documented in two SATSIE / NGI reports that will be followed by publications in refereed scientific journals.

Task 5.2 – Snow entrainment and mass balance: The investigation of the effects of entrainment of bed material on the velocity profile of the avalanching flow has progressed, with dedicated experiments carried out at the new granular chute C in Pavia (see Fig. 3.13). First results show the capability of the experimental set-up to capture the evolution of the velocity profile of the flow as the erosion process progresses (see Fig. 3.14). However, most of the experimental data collected in the last months still await

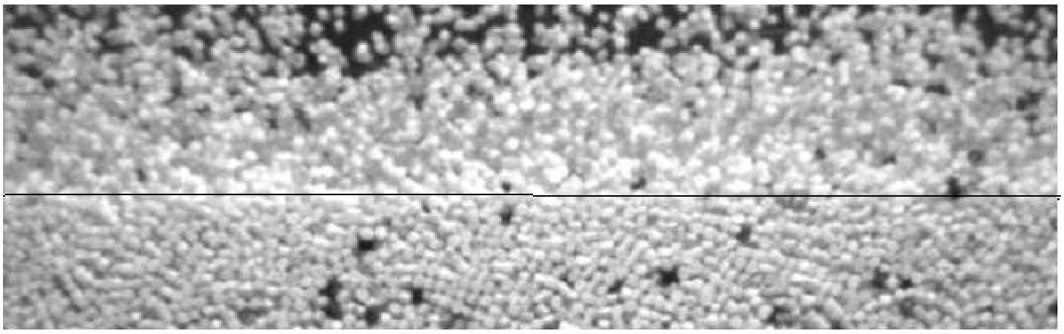

Figure 3.13: Typical frame from high-speed video of a granular flow over an eroding bed taken at chute C in Pavia. The line has been added to visualise the current interface between theflow and the bed.

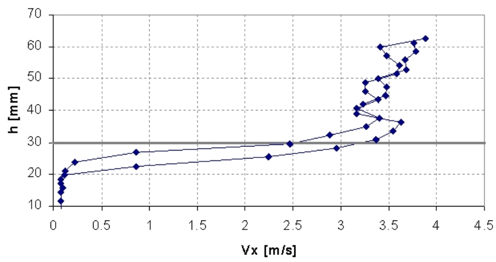

Figure 3.14: Two instantaneous velocity profiles obtained from the run shown in Fig. 3.13. The flow is quasi-stationary, as exemplified by the close similarity of the profiles that are just shifted vertically by the depth of material eroded between the two instances.

processing and analysis.

Task 5.3 – Analysis of the generation of powder snow avalanches: Two more papers have been written developing powder snow avalanche models and applying them to field data. Turnbull et al. (2006) develop the Kulikovskiy–Sveshnikova–Beghin model and give a new derivation demonstrating its universality. The model is then compared with field data. This paper has been accepted for publication in the Journal of Geophysical Research. Another paper (Turnbull and McElwaine, 2006) has focused on plume models comparing these to video data. This has been submitted to the Journal of Glaciology.

Task 5.4 – Interaction of avalanches with obstacles: A workshop on the design of snow avalanche dams was held at Weissfluhjoch in Davos, Switzerland on 13–16 March 2006. The workshop, which was organised by SLF in Davos, was attended by several SATSIE participants. It provided a forum for comparison of design criteria for the SATSIE handbook with criteria under development at SLF based on laboratory chute experiments. The design criteria that are being developed by the two groups are fundamentally similar although there are some differences. The formulation of the design criteria will be discussed further in an ongoing collaboration between SLF and the SATSIE Handbook writing team. Discussions at the meeting provided important input to the compilation of the SATSIE dam design handbook.

As a part of the formulation of design criteria for avalanche dams for the SATSIE handbook, available field observations about avalanche run-up on natural terrain obstacles and man-made dams from Norway, Iceland and France have been collected into one data set and used to validate the new design criteria (The Satsie Handbook writing team, 2006). A report about the Norwegian part of the data set is in preparation at NGI (Domaas and Harbitz, 2006).

Closed analytical expressions for the run-up corresponding to the shock thickness upstream of catching and deflecting dams have been derived (The Satsie Handbook writing team, 2006). These expressions simplify the application of shock dynamics to practical problems such as the design of avalanche dams.

Run-up and overrun data from the catching dam at Ryggfonn have been analysed in terms of the design of avalanche dams (Gauer and Kristensen, 2005a). The full-scale data from Ryggfonn are partly inconsistent with other evidence for run-up from natural obstacles and results of laboratory experiments and highlight the currently incomplete understanding of the dynamics of avalanche flow against dams and other obstacles.

Measurements of impact pressure from Ryggfonn (Gauer et al., 2006), together with results of laboratory experiments (Hauksson et al., 2006) and existing design guidelines about impact pressures from Norway and Switzerland have been interpreted and a new suggestion for the calculation of impact pressures on obstacles formulated for the SATSIE dam design handbook.

Task 5.5 – Report on the validation of new models: Expressions for run-up of avalanches, which have been formulated on the basis of laboratory experiments and theoretical analyses within CADZIE and SATSIE, have been checked against available field observations of run-up of avalanches on terrain obstacles and dams. A report about this validation is near completion (The Satsie Handbook writing team, 2006) and has been circulated within the SATSIE handbook writing team in draft form.

The delay in the definitive formulation and numerical implementation of NGI's new model made validation of the model within SATSIE obsolete. This task will, however, have to be fulfilled in the near future before the model can be used in practical work. It is clear that only a small portion of avalanche measurements and observations can be used to that purpose because most did not distinguish between the fluidised or saltation layer and the dense core. The most promising data are recent measurements from Vallée de la Sionne and Ryggfonn as well as observations carried out in the Davos area, within another project, by one of the project participants (D.I.).

3.5.3 Suggestions for future work

Task 5.1 ETNA will extend the research on flow rheology by combining Molecular Dynamics simulation that take into account cohesion and polydisperse material with results from the annular rheometer and measurements at the Col du Lautaret path. The latter will be equipped with the same sensors as the Col du Lac Blanc chute.

Development of NGI's new model and its numerical implementation must be accelerated. Due to its novelty and the lack of explicit consideration of the fluidised layer in all but the most recent field reports, validation must involve critical assessment of data sources to be used. Once these issues have been resolved satisfactorily, the model should be extended to also describe the suspension layer and entrainment/deposition from the snow cover.

Task 5.2 Further development of entrainment modelling will require a continued dialogue between detailed experiments and theoretical analysis. A first objective for future experiments could be to thoroughly test the entrainment/deposition model proposed by Naaim et al. (2003) in quasi-stationary conditions for different types of bed materials. Experimental verification of the relations developed by Issler and Jóhannesson (2006) should also be feasible. On the theoretical side, the mechanisms proposed by Gauer and Issler (2004) need to be studied further in order to determine the experimental signatures of their occurrence for comparison with measurements and to model them in terms of the variables available in depth-averaged flow models. Finally, meaningful mappings from snow properties that can easily be estimated in the field or in the process of hazard mapping to the parameters of the entrainment model should be established.

Task 5.3 One of the greatest unknowns in current models is how to correctly account for lateral spreading of powder snow avalanches. In fact in analytic models this is nearly always ignored. Laboratory experiments are needed, either in air or water, to study this and develop and verify models.

Task 5.4 The compilation of the SATSIE dam design handbook has highlighted our incomplete understanding of the dynamics of avalanche flow against obstacles. Laboratory experiments and theoretical analysis have advanced our understanding of these dynamics, but measurements of overrun and velocity of avalanches over the dam at Ryggfonn indicate that avalanches are under some conditions able to scale dams quite easily. Data about run-up of natural avalanches on obstacles and man-made dams is also partly inconsistent and cannot be explained within one conceptual framework. These inconsistencies may perhaps be partly explained by the uncertainty of the data and back-calculated velocities and flow depths, but this is unlikely to be the only explanation. Further full-scale experiments and further theoretical analysis are required to improve this unsatisfactory situation.

ETNA plans to build a large laboratory chute to study the interaction between flows and structures. The similarity criterion for structures requires large flow dimensions.

Task 5.5 As described under the previous item, further work is critically needed to resolve problems in the current understanding of the dynamics of avalanche flow against obstacles. Validation of models and theoretical concepts with observations from full-scale experiments is particularly important in this regard.

Model validation has to be considered a continuous task as long as avalanche models contain so many uncertainties and approximations. With the advent of more physically realistic models, measuring the runout distance and the velocity at one point is no longer sufficient to test the specific predictions of these models. "Complete" measurements including velocity evolution along the path, velocity distribution along the avalanche body, vertical velocity profiles, entrainment rates, flow regimes, and densities are

needed, requiring a very well equipped test site. It would be highly desirable to build up a database of avalanche events that fulfil some minimum quality requirements for use in model validation, and to make it accessible to all interested parties. The database from SATSIE experiments will hopefully serve as a crystallisation point for such an initiative.

3.6 WP 6 – Data sharing and dissemination of results

3.6.1 Objectives for the reporting period

Task 6.2 – Database maintenance and data back-up: Archive all new experimental data.

Task 6.3 – Maintenance of project website: Keep the website up-to-date and informative.

Task 6.4 – Handbook on dam design: Completion of handbook.

Task 6.5 – User manuals for new numerical models: Completion of user manuals.

Task 6.6 – European Summer University 2006, advanced course: Resolve logistic aspects. Start preparation of course material.

3.6.2 Achievements during the reporting period

Task 6.2 – Database maintenance and data back-up: Data from the winter 2005/2006 has been added to the archive, which now contains 106 GB of data. The data archive contains the following:

- 5 films of natural avalanches, two from Ryggfonn (Norway) and one each from Cervi (Spain), Roies (Spain) and Lautaret (France).
- 861 film clips and 889 air pressure datasets from powder snow avalanche experiments undertaken as part of Task 5.3 (Powder snow avalanches), Task 2.2 (Video analysis) and Task 2.3 (Air pressure sensors).
- The datasets from Hákonardóttir's thesis (Task 5.4 – Interactions with dams, impact loads) and Task 3.6 (Chutes in Bristol).
- 4 pulsed Doppler radar datasets from Ryggfonn (Task 2.1 – Data-analysis techniques for radars) and Task 1.1 (Radar techniques).
- 21 datasets from Ryggfonn (Task 3.1) with impact pressure and geophone data covering 2002–2006. In addition seismic data (Tasks 1.7 and 2.6) for winter 2004/2005 (4 events) and laser scan data for winter 2005/2006 (8 files from one event).
- There are 12 datasets from the Pavia chute comprising several thousand images from the high-speed camera, Task 5.2 (Snow entrainment and mass balance), Task 3.5 (Chutes in Pavia).

The datasets are freely available over the internet (http://www.damtp.cam.ac.uk/user/jnm11/satsie_data_archive/satsie_index.html), in the CDF (Common Data Format). The web site also includes explanatory notes, a description of the formats and naming scheme as well as Matlab software. The archive will be maintained in Cambridge for the next few years and a copy transferred to NGI for permanent storage.

Task 6.3 – Maintenance of project website: The SATSIE web site is continuing to act as a forum for the dissemination of information to both project members and the general public. The site has now had 4000 visits and the main new addition in the last six months include minutes of meetings in Reykjavík and Seyðisfjörður, the 3rd Annual Report as well as a page for Dr Peter Gauer at NGI (http://www.leeds.ac.uk/satsie/gauer.html). In addition, because of the large file size of many of the project deliverables, the private area of the web site has been a convenient method for transferring draft versions of these to project members.

As the project reaches a conclusion, the final version of project deliverables will be moved from the private area into the public domain and the "project description" section of the web site will be

finalised to include the main scientific results from the SATSIE project. Hence, the web site will act as a permanent public record of the achievements of the project.

Task 6.4 – Handbook on dam design: A draft version of the handbook and a report about the dynamic and observational background of the proposed design criteria have been written and are included in the appendix to document the present stage of the work. Beyond the design of catching and deflecting dams, recommendations are also given concerning the functioning and dimensioning of braking mounds and the estimation of the design loads (including their vertical variation) on man-made obstacles. It has been decided not to publish the handbook at the end of SATSIE but to wait until consensus has been reached among the authors on a few open questions.

Task 6.5 – User guides for new numerical models: For the introduction of ETNA's new model MN2L to practitioners of the Service RTM, a user manual was written in French. In the course of the reporting period, this was translated into English. Both versions can be found in the Appendix.

Writing of a user manual for NGI's D2FRAM could not be started because the model is not yet operational. This task will be completed as soon as enough experience inapplicationation of the model to practically relevant situations has been accumulated.

Task 6.6 – European Summer University course: The SATSIE consortium contributed in a major way to the European Summer University (UEE) course on Natural Hazards, Session on Snow Avalan-corganisednized by the PGRN (Pôle Grenoblois d'Etudes et de Recherche pour la Prévention des Risques Naturels). We gave advanced courses on avalanche modelling, we put some of the models developed by the consortium at the disposal of the participants and we conducted hands-on practical sessions of back-calculation of events and avalanche mapping.

This practical experience reinforced our conviction that numerical models are indeed very useful in the expertise work on snow avalanches. Many questions cannot be solved satisfactorily without using this kind of tools. Important questions such as the complex case of mixed avalanches cannot be addressed at the level of courses given at the European Summer University. This is why we decided to supplement the UEE courses by an specialised course on avalamodellingeling oriented towards practical use of advanced models. We dedicated a part of the last year to (i) consulting experts on the interest of such a course, and (ii) appoint a scientific committee and set up the course program.

We asked the PGRN to organise these courses and prepare a budget. The cost of the organisation was estimated at 12 kEuro. This part can be covered by the tuition fees. But the salaries of the instructors, which represent the main part of the costs, is too high to be covered by the fees. The exchanges we had with some experts and engineering services showed that if the cost is too high we will have too few students. This is why we fixed the price to 500 Euro and looked for additional financing from public institutions such as the Department of Isère and the EU in the framework of an RTN project. Confronted with the administrative processing times of our grant applications, we decided to organise these courses immediately after the next regular session of the UEE in September 2007.

3.6.3 Suggestions on valorisation of the results beyond the project duration

The project website has served our purposes well. Given that collaboration between the partners will continue beyond SATSIE on an informal level, further maintenance and additions to it will be very useful. We do not know how often and by whom outside the consortium the site was visited. An effort to publicise it beyond the consortium could turn it into a vehicle for communicating results from SATSIE and subsequent work to state institutions, practitioners and the interested public.

On a more technical level, the experimental database built up during SATSIE could be used to store, back-up and share new experimental results among the partners and the interested public. The usefulness of

the archive could of course be enhanced if other avalanche research institutions were to make their data accessible in a compatible format or even contribute to this database.

Work on the Handbook on dam design has revealed that our present knowledge is after all still insufficient to write the definitive guidelines on the topic that could be turned into a standard. Nevertheless, much has been achieved and the product of these efforts is eagerly awaited by practitioners. Therefore, after completion of the first edition, an informal agreement for monitoring adoption of the handbook in practice and all new developments in this field should be set up between the involved partners. Workshops or short courses open to practitioners and researchers could be an effective method for achieving this. The long-term goal should be to produce a second edition of the handbook when a sufficient amount of new knowledge has been gained.

In a very similar way, the new models should be publicised and their use in practice followed up upon as far as this is feasible from a financial point of view. European Summer University courses are very suitable for this purpose, but the perennial language problem in those courses needs to be solved and a sufficient source of financing found.

3.7 Socio-economic relevance and policy implications

The discussion of the socio-economic impact of SATSIE and its policy implications that was given in the 3rd Annual Report remains valid. We do not repeat it here but add a few specific remarks that reflect the progress of the project since the last Annual Report.

Monitoring and alarm systems: The new Doppler radar system has demonstrated its performance as a research instrument in Ryggfonn. Direct comparison with earlier data from AIATR's older radar highlighted the importance of having a larger number of shorter range gates and acquiring spectra much more rapidly than hitherto. AIATR has now decided to purchase such a radar.

The FMCW radar demonstrated its exceptional performance in laboratory tests. The continual degradation in the signal strength under the harsh conditions in the Ryggfonn soil does not put in doubt the concept of the device but must be understood and eliminated before the radar can be commercialised. Accordingly, development of a cheaper, less performant version has not begun yet. Some market research will be required to determine the optimal specifications and the likely number of systems that can be sold.

Understanding of the seismic properties of avalanches has made significant progress in SATSIE. In particular, the speed can now be determined fairly accurately from a series of simple geophones along the path, and the signal strength could be used to infer the size of the event. These achievements by themselves do not yet have significance beyond the basic research, but they might be combined with other developments aiming at avalanche activity monitoring of large areas. As more properties of avalanche events can be determined, detection will become more reliable and important additional information for avalanche warning services could be gained.

Improved knowledge on dam design: The joint work of IMOR and the University of Bristol on shock formation in the impact of granular materials on various types of obstacles represents a breakthrough in our understanding of the functioning of catching and deflecting dams as well as braking mounds. Even though many questions need to be studied in more detail still, it is clearly visible that the presently used, very crude dimensioning criteria will be superseded by a more complete theory. Fortunately, the new insights do not completely invalidate the design of existing dams, but they will allow a more thorough assessment of the hazard reduction achieved by such measures and help in optimizing the design of future dams. The societal benefit of these results lies not in their commercialisation, but in the added safety and the potentially lower costs of optimised designs.

A similar initiative, albeit at a somewhat smaller scale, has been taken in Switzerland by SLF. Due to contractual obligations of SLF, it will not be possible to completely merge the two efforts, but both the SATSIE partners and SLF agree that every effort should be made to exchange knowledge and experience on the topic and to strive for compatibility between the SATSIE handbook and the Swiss guidelines. This paves the way for a common European handbook (or guidelines) in the future.

Contribution to the education of avalanche professionals: Experience in France with the distribution of MN2L has shown how a numerical model that is sufficiently easy to use can overcome the deep-rooted reluctance of many avalanche professionals, who often do not have formal training at the university level, against the use of non-empirical tools. A carefully prepared introductory course, oriented towards their professional experience and needs, is essential in the process.

Professionals experienced in the use of earlier models have reacted enthusiastically to the SATSIE consortium's intention to organise an advanced European Summer University course. It will take place only after the end of SATSIE. Difficulties in obtaining adequate funding on short notice forced us to defer it from the originally targeted date of September 2006. This course will bring together avalanche practitioners from many European countries plagued with avalanches and will

be an excellent venue to foster exchange of experience across borders, contributing in this way, on an informal level, to more uniform procedures in the assessment of avalanche hazard.

3.8 Contributions by the consortium partners

Table 3.3 gives an overview of the main activities of the partners in each work package. More detail can be found in Sections 3.1–3.6. In the concluding period of SATSIE, the focus was on finishing the deliverables to make them ready for dissemination and collecting more data at Ryggfonn. The latter objective was largely defied by the weather conditions, however. As far as funding permitted, the chute experiments were also continued.

Correspondingly, the partners most intensely involved in the dissemination aspects of the project were the most active during this period, in particular SGUL, which had the responsibility for writing review articles and overview reports on the experimental results from SATSIE, and IMO in charge of coordinating the writing of the handbook on dam design. In contrast, INW's activities within the project were essentially terminated at the end of the last reporting period.

Partner		WP 1	WP 2	WP 3	WP 4	WP 5	WP 6
1	NGI	Debugging of FMCW radar		Site maintenance at Ryggfonn	Meas. of spont. aval. at Ryggfonn,1 campaign with artificial release	NIS2. Flow-regime changes	Handbook on dam design
2	IMOR			Site maintenance at Flateyri	Chute experiments with obstacles in Pavia	Shocks in granular flows, interpretation of run-up on natural obstacles	Handbook on dam design
3	SGUL		Development of methods for analysing fluctuations in time-series data		Chute experiments with obstacles in Pavia; editing D11 and D12	Statistical analysis of runout data; application of time-series methods to flow regime changes	Maintenance of SATSIE website
4	DAMTP	Improved design of air pressure sensor	Video analysis, opto-electronic sensors. Preliminary analysis of impact data	Improved chute for flows on very steep slopes	Exp. on powder snow avalanches. Air pressure at VdlS	Theory of powder snow clouds on steep slopes	Maintenance of SATSIE data archive
5	AIATR				1 campaign at Ryggfonn		Drawings for handbook on dam design
6	INW	Debugging of FMCW radar			Analysis of Doppler radar data		
7	ETNA	Redesign of snow rheometer			Snow chute experiments	Further development and testing of N2L, rheological studies	Work on handbook on dam design
8	DIIA		Video analysis techniques	New chute for entrainment studies	Chute exp. on flow regimes, entrainment, impacts		First Italian university course on snow and avalanches
9	DGG	Improvements of data acquisition system	Seismic methods for velocity and size measurements		Measurement, analysis of seismic signals at Ryggfonn		

Table 3.3: Overview table of contributions of the consortium partners to each work package.

3.9 Discussion and conclusion

Much of what was said in the corresponding section of the third Annual Report is still valid today and will not be repeated here. Instead we focus on the new developments that have taken place, and the changes in the assessment of achieved results and open questions.

In the area of sensor development, the major disappointment was that all the FMCW radar systems again showed the same symptoms of continually degrading output performance, despite the much improved corrosion protection applied during the summer. Taking advantage of the scarcity of snow at Ryggfonn during the winter 2005/2006, the antennas were replaced on-site by an improved design because it was suspected that the original antennas might absorb water, which would damp the output power very substantially. When output power still remained very low, it was decided to reanalyse the entire system for possible sensitivity to harsh environmental conditions in the summer of 2006.

Despite these problems, the development should be continued. FMCW radar is not the only sensor type that can measure velocity profiles in full-scale snow avalanches, but it is the only one to achieve this without disturbing the flow. At the same time, the front velocity, the flow depth and the erosion rate are measured and a qualitative indication of the density profile is obtained. Detailed analysis of the Ryggfonn data collected during SATSIE evidenced time and again how much could be gained if this extra data were available.

Such data would indeed be most helpful in the development and validation of D2FRAM, NGI's new dynamic model for describing avalanches that can undergo transitions between the dense and fluidised flow regimes. However, by themselves they are not sufficient to verify or reject all aspects of the complex rheology at the basis of this model, and to determine the density dependence of the basic model coefficients. The rotating-cylinder rheometer developed by ETNA could provide some of this data while the rest should be obtained from a future series of chute experiments carefully designed for this purpose. While much recent work at Col du Lac Blanc and also in Pavia used steady flows, which are significantly easier to analyse, the challenges of measuring velocities and densities as well as their fluctuations at several locations in transient flows will need to be addressed in order to obtain the full picture of the flow regimes of granular gravity mass flows. Experience from the small-scale laboratory studies of the onset of suspension flow, i e. powder-snow avalanches, by DAMTP in collaboration with SLF should be very helpful in this task. The development of novel statistical analysis methods for detecting flow-regime transitions that would go unnoticed by visual observation alone (Keylock, 2005, 2006a,b) may also prove very important in this context.

Further chute experiments will also be instrumental in studying erosion processes in more detail. The most recent series of measurements with dry granular materials in Pavia showed that the modification of the velocity profile due to entrainment, predicted by the theoretical study of Issler and Jóhannesson (2006), should be measurable in appropriately designed experiments if the entrainment rate is not too small.

Another important source of information on the internal dynamics of full-scale snow avalanches could not yet be tapped for the lack of access to suitable data, namely high-frequency measurements of impact pressure on relatively small load cells. As shown by Schaer and Issler (2001), single impacts can be resolved in the fluidised layer and the particle sizes, velocities and densities reconstructed to some degree. This reconstruction is a complex task and there is large uncertainty in the preliminary results, but the insight that can potentially be gained justifies additional research. Unfortunately, the very large load plates installed at Ryggfonn are unsuitable for this purpose.

In the last eight months of SATSIE, much of the experimental, theoretical and disseminational activity was focussed on the interaction of avalanches with obstacles. The chute experiments with dry granular materials, conducted at high Froude numbers, appear to be well explained by shock theory for incompressible media; the granular avalanches realise the hydraulic jumps predicted even more precisely than

water flows. Snow avalanches, being more compressible, should dissipate kinetic energy even more rapidly and form very sharp and somewhat lower jumps. Experiments at the snow chute at Col du Lac Blanc designed to study this question have just been started and will provide much needed data on the validity of the shock dynamics for supercritical snow slides at comparatively low Froude numbers.

The reanalysis of data from avalanches that overran the Ryggfonn dam (Gauer and Kristensen, 2005a) will also prompt further theoretical investigations and comparison with other data. These authors found that there is an apparently linear relationship between the kinetic energy of the approaching avalanche and the overrun length (both quantities being non-dimensionalised in units related to the dam height). Taken at face value, the obtained relation says that only relatively little energy is dissipated during the impact on the dam—if the avalanche is able to overtop the dam. Applying the method to the Bristol and Reykjavík laboratory experiments, the relation appears mildly non-linear, which may be a consequence of the different geometries. The disquieting queston arises: Are catching dams much less effective than hitherto assumed? Reassuring, but partly inconsistent, evidence from natural snow avalanches that have hit dams and natural obstructions does, however, indicate that natural snow avalanches have in several documented cases been affected by obstructions to a larger degree than the Ryggfonn data seem to imply. Results from SATSIE have raised this question at the end of the project without being able to conclusively answer them. Perhaps a partial answer lies in another central topic of SATSIE, namely the fluidised flow regime: The low-density, high-velocity front of a dry-snow avalanche may often be able to overtop a dam that is designed for the slower dense part, but the mass fraction that overflows the dam is relatively small and the pressures exerted by that mass are significantly lower than if the dam were absent and the dense-flow part had reached that area. However, this is a speculation at present that needs to be tested in future, more detailed measurements.

As is probably true for all genuine research projects, SATSIE has answered certain questions, but raised even more new ones. The project's fundamental approach of tackling practical questions, not with presently fashionable socio-economic tools, but instead to focus on the mechanical questions that are at the heart of the phenomena and provide the foundation for technical solutions, has proved rewarding in this case. Much of the work in this project could only be done in close international collaboration, and even those pieces that could be done by smaller groups attained more significance when put into the wider context of this co-ordinated research effort.

Chapter 4

Technology Implementation Plan

Project Summary

Project Contract Number:	EVG1-CT-2002-00059
Commission Officer Name:	Denis Peter
Commission Officer E-mail:	Denis.Peter@cec.eu.int
Coordinator Name:	Karstein Lied
EC program:	EESD
Title of project:	Avalanche studies and model validation in Europe
Acronym:	SATSIE
Website:	http://www.leeds.ac.uk/satsie
Programme type:	5th FWP (Fifth Framework Programme)
Project start date:	01 Oct 2002
Project end date:	31 May 2006

Executive summary

Original research objectives:
The SATSIE project will contribute to sustainable development in Europe's mountain regions through: (i) substantially improved tools for hazard mapping, (ii) design criteria for protection dams and (iii) low-cost radar systems for monitoring and managing avalanche hazard in critical locations. In addition, the intense collaboration will further improve the professional level of the participating institutions and their employees, many of which are also very active in hazard mapping and various other types of consulting work.

The emphasis of SATSIE is on improving the physical basis of dynamical avalanche models, in particular on modelling the flow regimes and the rates of snow entrainment and suspension.

To this end, experiments are carried out at a full-scale avalanche test site (Ryggfonn in western Norway, operated by NGI for more than 20 years) and in laboratory chutes located in Pavia, Bristol and at Col du Lac Blanc (Haute-Savoie, France, 2900 m a.s.l.), where small-scale experiments can be conducted with natural snow. Previously developed impact models will be validated through measurements at full-scale dams.

For research within SATSIE and beyond as well as for monitoring purposes in practical applications, novel sensors measuring important parameters inside the flowing avalanche are developed: frequency-modulated continuous-wave radar, range-gating Doppler radar, an air-pressure sensor for measurements under harsh environmental conditions inside avalanches, etc.

Intensive collaboration between partners and dissemination of results through handbooks and courses

will bring increased competence to all countries concerned by avalanches.

Expected Deliverables:

FMCW radar:
A novel design of frequency-modulated continuous-wave radar in the C-band will be developed and four systems installed at Ryggfonn. They will feature much higher temporal and spatial resolution as well as a much narrower beam than existing designs, allowing the measurement of flow depths, snow entrainment rates and velocity profiles (when used in pairs). Low-cost systems may be derived for monitoring the snow cover in otherwise inaccessible avalanche release areas.

Doppler radar:
A new Doppler radar will be built and installed at Ryggfonn, improving on the design of existing avalanche radars and providing better spatial resolution at a lower cost. Such systems may form a component in an alarm system for exposed traffic routes, monitoring incipient motion in an avalanche track or verifying the success of artificial release attempts.

Air pressure sensor:
A special sensor for measuring the static air pressure in powder-snow avalanches will be developed to deduce their shape and velocity. It must be able to operate under harsh winter conditions and withstand high mechanical loads. The strong direction dependence of the classic Pitot design is circumvented by judiciously combining pressure measurements in different directions.

Improved LED sensors:
A measurement technique for velocity profiles in granular flows based on correlating the fluctuating signals of pairs of closely spaced small LED/photocell sensors will be improved for better precision and higher spatial resolution.

Improved snow rheometer:
A rotating-drum rheometer for testing debris-flow slurries and soils will be adapted to the conditions of snow-rheology measurements over a wide range of shear rates. Particular care will be needed due to the compressibility of the snow and its tendency to form shear bands where all the shear is localised.

Handbook on dam design:
Insight gained from recent laboratory and full-scale experiments on avalanche-dam interaction will be presented and discussed. This knowledge is used to deduce new dimensioning criteria and compare them to the traditional methods. Based on this, recommendations are given for the procedure to follow in assessing the suitability of different dam types in a specific situation and in the overall design of a dam. Several examples illustrate the main points.

Avalanche dynamics models:
Novel models describing the flow of snow avalanches will be formulated mathematically and implemented as computer codes for use in avalanche hazard mapping and the planning of protective measures. The models will incorporate the new results from chute experiments and full-scale measurements, in particular with respect to the dependence of friction on flow height and velocity, the emergence of different flow regimes (dense frictional flow vs. fluidised collisional flow), and the mechanisms and rates of snow entrainment from, and deposition to, the snow cover. Both 1D and 2D depth-averaged implementations are envisaged.

Reports:

- Summary publication on sensor design and data analysis techniques
- Update of SAME overview report on European avalanche test sites
- Documentation of instrumentation scheme and installation work at the selected sites

- Report on experimental results (in two parts: (1) small-scale avalanche processes, (2) full-scale avalanche processes)
- Report on avalanche/dam interaction measurements (in three parts: (1) catching dam at NGI's Ryggfonn site, Norway; (2) deflecting dam at Flateyri, Iceland; (3) combined braking-mound / deflection-dam / catching-dam system at Taconnaz, France)
- Reports on avalanche modelling implementing (a) flow regime transitions, (b) snow entrainment and deposition, (c) generation of powder snow avalanches, (d) interaction of avalanches with obstructions, and (e) a summary report about the validation of the models
- User manuals for advanced models in avalanche hazard mapping

Papers:
The main results from the project will also be published as articles in refereed scientific journals and presented at major international conferences, with summary papers in the corresponding proceedings.

European Summer University course:
The targeted audience consists of advanced students specialising in natural hazards issues and experienced engineers (outside academia) active in avalanche hazard mapping and consulting. The intensive course will give an overview of the present knowledge of avalanche dynamics (gained particularly during SATSIE), introduce the modern concepts of hazard mapping, discuss the new avalanche flow models and apply them to real-world problems in the surroundings of the course location, including substantial field work. The participants will be made aware of the different national guidelines and regulations concerning avalanche hazard mapping. The course instructors will be recruited from the staff of the consortium members.

Project's actual outcome:

FMCW radar:
A prototype was deployed at Ryggfonn in the beginning of 2004, but communication problems prevented the collection of data. Four systems with improved main-circuit boards were successfully installed in September 2004. Signal quality deteriorated strongly in the course of the winter. In the fall of 2005, the systems were reinstalled with improved corrosion protection, but signal quality loss was experienced again despite an improved antenna design. In 2006 the design is being scrutinised for its behaviour in cold, humid environments, and tests will again be performed in the winter 2006/2007.

Doppler radar:
The system was delivered to NGI by INW in June 2004 and installed in Ryggfonn in September 2004, following successful tests at NGI. The system performed very well during an artificially triggered avalanche release in April 2005; some modifications were subsequently applied to the analysis software.

Air pressure sensor:
A first design was implemented in 2003 and installed on the 20 m high mast at the Swiss Vallée de la Sionne test site in the autumn of 2003. Data from several avalanches were successfully collected and analysed. On the basis of these results, a modified design was installed. In the winter 2004/2005, icing in the interior destroyed the device, which led to a redesign of the sensor. New tests have to await the availability of financing for constructing a new prototype.

Improved LED sensors:
A first series of sensors were developed in late 2002 and has been successfully used at Col du Lac Blanc since the winter 2002/2003. A yet smaller system capable of measuring velocity profiles in the bottom-most centimetres of the flow was subsequently developed and has been successfully used since 2003/2004.

Improved snow rheometer:
A first series of tests revealed that compression of the snow and the formation of shear bands did not allow valid rheological measurements on snow. An improved design with an inflatable inner wall of the shear cell attempts to compensate for the compression. Tests during the winter 2005/2006 were not satisfactory yet, so an improved pressure control will be implemented and tested.

Handbook on dam design:
A draft version has been produced. Work on the final version is ongoing.

Avalanche dynamics models:
The model MN2L developed by ETNA has been designed, implemented as 1D and 2D 2-layer codes, described and extensively tested. It incorporates results from granular and snow chute experiments for the dependence of the effective friction coefficient on velocity and flow height, and also features an entrainment/deposition model based on the difference between the shear stress exerted by the avalanche and the strength of the bed that also takes into account the acceleration of the eroded mass in agreement with the velocity profile.

At NGI, extensions of the Norem-Irgens-Schieldrop model to 2D depth-averaged flows with variable density are studied in order to describe the formation of a fluidised zone of flow. Also, the effects of terrain curvature are taken into account in a more accurate fashion than in earlier models, allowing better modelling of avalanche flow in strongly curved paths or over hummocky terrain. The model is being implemented with a state-of-the-art shock capturing numerical scheme in 2006.

Reports:
A list of reports and scientific papers written in the context of the project is available from the SATSIE website (http://www.leeds.ac.uk/satsie/publications.html), from where many of the papers can also be downloaded.

European Summer University course:
In response to the schedule of the cycle of basic courses offered by the Pôle Grenoblois d'Etudes et de Recherche pour la Prévention des Risques Naturels (PGRN), it was decided to participate in the scheduled 2004 course on snow avalanches and to offer an advanced course on the modelling of avalanches in 2007, i.e., after the closure of SATSIE. This will have the advantage that more extensive experience with both new models will be available.

Broad dissemination and use intentions for the expected outputs:

European Summer University:
A course for advanced students in fields relevant to natural hazards and for practitioners working in natural risk mitigation and management. Enrolment in the 2004 course was 35–40 persons, expected enrolment in the 2007 advanced course is 30–50 persons.

Distribution of handbook on dam design to all interested parties.

Application of new models in hazard mapping:
The new models will be applied by several project partners (NGI, IMOR, AIATR, ETNA, DIIA, DGG) in their own consulting and hazard mapping work. Besides this, at least the 1D version of MN2L will be distrubuted free of charge to interested practitioners and institutions.

Application of new design criteria for dam construction:
Dam design is done by several of the consortium partners (NGI, IMOR, ETNA) or by their spin-offs (DIIA). It is hoped that the availability of the handbook will lead to the adoption of these improved design criteria by other agencies, practitioners, etc.

Handbook on Avalanche Dam Design – 32938

Partner(s) owning this result:

- Norwegian Geotechnical Institute – Karstein Lied
- Icelandic Meteorological Office – Tómas Jóhannesson
- University of Leeds – Christopher Keylock
- University of Cambridge, Department of Applied Mathematics and Theoretical Physics – Jim McElwaine
- Federal Forest Office and Research Training Centre for Forests, Natural Hazards and Landscape – Lambert Rammer
- Graz University of Technology, Inst. für Breitbandkommunikation – Helmut Schreiber
- Centre National du Machinisme Agricole, du Génie Rural, des Eaux et des Forêts – Erosion torrentielle, neige et avalanches – Naaim Mohamed
- Università degli Studi di Pavia – Dipartimento di Ingegneria Idraulica e Ambientale – Massimiliano Barbolini
- Universitat de Barcelona – Emma Suriñach Cornet

Category: A – results usable outside the consortium.

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Summary:

Handbook on deflection and catching dam design: Different types of protection dams and their basic principles of operation are presented. Insight gained from recent laboratory and full-scale experiments is presented and discussed. This knowledge is used to analyse the merits and shortcomings of newly developed dimensioning criteria and compare them critically to the traditional methods. As part of this, the estimation of impact pressures and loads is also discussed in view of recent measurements. Based on these foundations, recommendations are given for the procedure to follow in assessing the suitability of different dam types in a specific situation and in the overall design of a dam. Several examples illustrate the main points.

Subject descriptors:

* 105 – CIVIL ENGINEERING (INCL. PAVEMENTS AND STRUCTURES)
* 129 – COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL
* 280 – HAZARDS: NATURAL
* 347 – LAND USE PLANNING/LANDSCAPE/LANDSCAPE ARCHITECTURE

Potential offered for further dissemination and use:

The Handbook on Dam Design summarises know-how from a number of the leading research institutions on snow avalanches with regard to field observations, full-scale and laboratory measurements, theoretical analysis and practical experience in the construction of protection dams. It fosters the application of best practice throughout Europe and the emergence of common European avalanche dam design guidelines.

The consortium partners contributing to this Handbook are also available for consultancy on the choice and design of mitigative measures.

Profile of additional partner(s) for further dissemination and use:

– Public agencies involved in the planning and/or financing of protection dams: (i) Apply the procedures and design criteria (or encourage their application). (ii) Give feedback to the authors regarding the experience in the construction of dams. (iii) Provide information on observed avalanches impacting on dams.
– Private consultants involved in the planning of protection dams: (i) Apply the procedures and design criteria. (ii) Give feedback to the authors regarding experience in the construction of dams. (iii) Provide information on observed avalanches impacting on dams.

Software suite for analysis of avalanche videos – 32939

Partner(s) owning this result:

– University of Cambridge, Department of Applied Mathematics and Theoretical Physics – Jim McElwaine

Category: A – results usable outside the consortium

Contact person for the result:

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Summary:

Matlab and C software suite for analysing video images. The software has been successfully used on ping-pong ball avalanches, snow avalanches and laboratory experiments. It is designed for fixed cameras and assumes that the flow only arrives at each point once. It is based on a temporal change-point method that generated the first arrival times of the front so that the level sets are the flow contours. The package includes software for camera calibration and conversion to world coordinates on geometric surfaces and digital terrain models.

Subject descriptors:

* 130 – COMPUTER TECHNOLOGY/GRAPHICS, META COMPUTING

Documents:

Documentation type:	Proceedings paper
Details:	J. N. McElwaine (2004). Image Analysis For Avalanches. In: X. Y. Z. (editor), Proc. ...
Status:	Public

Application sectors:

* 33 Manufacture of medical, precision and optical instruments. . .
* 73 Research and development

Current stage of development:

Results of demonstration trials available

Software suite for analysis of correlations from pairs of LED/photocell sensors for determining velocity profiles in avalanche flows – 32940

Partner(s) owning this result:

- University of Cambridge, Department of Applied Mathematics and Theoretical Physics – Jim McElwaine

A: results usable outside the consortium

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Summary:

A package of Matlab functions for calculating velocities from the time lag between sensors. These are usually opto-electronic. Standard techniques are included such as fixed windows as well as continuous lag calculation and matched filtering. Error estimated can be calculated as well as 2d vector velocities.

Subject descriptors:

* 129 - COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL

Documents:

Documentation type :	"Calculation of Two-Dimensional Avalanche Velocities From Opto-Electronic Sensors"
Details	paper
Status:	Public

Application sectors

* 73 Research and development

Current stage of development:

Results of demonstration trials available

Summary of avalanche seismic detection installation – 32941

Partner(s) owning this result:

- Universitat de Barcelona – Emma Suriñach Cornet

Category: A – results usable outside the consortium

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Summary

Report describing the avalanche seismic detection equipment installed in Ryggfonn. The main purpose of the seismic installation is presented. Description of actual configuration and distribution of the seismic equipment (sensors and DAS) in Ryggfonn. Technical specifications of the seismic equipment and current acquisition parameters.

Subject descriptors:

* 172 – EARTH OBSERVATION TECHNOLOGY AND INFORMATION EXTRACTION
* 269 – GEOPHYSICS, PHYSICAL OCEANOGRAPHY, METEOROLOGY, GEOCHEMISTRY, TECTONICS
* 331 – INSTRUMENTATION TECHNOLOGY
* 431 – NOISE AND VIBRATIONS

Documents:

Documentation type :	Report
Details	Internal Report
Status:	Confidential

Application sectors:

* 75 Public administration and defence; compulsory social security
* 73 Research and development

Current stage of development:

Prototype/demonstrator available for testing

Calculation of avalanche speeds using seismic signals – 32942

Partner(s) owning this result:

- Universitat de Barcelona – Emma Suriñach Cornet

Category: A – results usable outside the consortium

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Summary:

In this paper a new method to obtain avalanche propagation speeds using seismic methods is presented. Since the damage produced by the avalanche depends primarily on the size and on the speed of the avalanche the knowledge of these parameter is therefore crucial for estimating avalanche induced hazard to the inhabited mountain areas.The method of avalanche speed determination presented in this paper is based on cross-correlation and time-frequency analysis techniques. The data used in this study came from Ryggfonn (Norway) avalanche experimental site operated by the Norwegian Geotechnical Institute (NGI).

Subject descriptors:

* 172 - EARTH OBSERVATION TECHNOLOGY AND INFORMATION EXTRACTION
* 280 - HAZARDS: NATURAL
* 347 - LAND USE PLANNING/LANDSCAPE/LANDSCAPE ARCHITECTURE
* 431 - NOISE AND VIBRATIONS

Documents:

Documentation type:	Paper
Details	Submitted to CRST
Status:	Public

Application sectors:

* 73 Research and development

MN2L-1D – a two-layer avalanche simulation model for mixed dry-snow avalanches, including an advanced entrainment/deposition model – 32943

Partner(s) owning this result:

- Centre national du machinisme agricole, du génie rural, des eaux et des forêts, Erosion torrentielle, neige et avalanches – Mohamed Naaim

Category: A – results usable outside the consortium

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Subject descriptors:

* 43 – APPLIED PHYSICS
* 128 – COMPUTATIONAL PHYSICS
* 129 – COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL
* 173 – EARTH SCIENCE, EARTH OBSERVATION/STRATIGRAPHY/ SEDIMENTARY PROCESSES
* 216 – EROSION

Documents:

Documentation type :	Paper by Naaim et al. (2003)
Details	Naaim, M., T. Faug and F. Naaim-Bouvet. 2003. Dry granular flow modelling including erosion and deposition. *Surveys in Geophysics* **24** (5/6), 569–585.
Status:	Public

Documentation type :	Paper by Naaim et al. (2004)
Details	Naaim, M., F. Naaim-Bouvet, T. Faug and A. Bouchet. 2004. Dense snow avalanche modeling: flow, erosion, deposition and obstacle effects. *Cold Regions Science and Technology* **39**, 193–204.
Status:	Public

Application sectors:

* 75 Public administration and defence; compulsory social security
* 73 Research and development

Current stage of development:

Other: Software finished. Results of validation available.

MN2L-2D – a 2D two-layer avalanche simulation model for mixed dry-snow avalanches, including an advanced entrainment/deposition model – 32944

Partner(s) owning this result:

- Centre national du machinisme agricole, du génie rural, des eaux et des forêts, Erosion torrentielle, neige et avalanches – Mohamed Naaim

Category: B – results usable exclusively within the consortium

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Subject descriptors:

* 43 – APPLIED PHYSICS
* 128 – COMPUTATIONAL PHYSICS
* 129 – COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL
* 173 – EARTH SCIENCE, EARTH OBSERVATION/STRATIGRAPHY/ SEDIMENTARY PROCESSES
* 216 – EROSION

Documents:

Documentation type:	Paper by Naaim et al. (2003)
Details	Naaim, M., T. Faug and F. Naaim-Bouvet. 2003. Dry granular flow modelling including erosion and deposition. *Surveys in Geophysics* **24** (5/6), 569–585.
Status:	Public

Documentation type:	Paper by Naaim et al. (2004)
Details	Naaim, M., F. Naaim-Bouvet, T. Faug and A. Bouchet. 2004. Dense snow avalanche modeling: flow, erosion, deposition and obstacle effects. *Cold Regions Science and Technology* **39**, 193–204.
Status:	Public

Application sectors:

* 45 Construction
* 75 Public administration and defence; compulsory social security
* 73 Research and development

Current stage of development:

Other: Software finished, validation results available

Range-gating (pulsed) Doppler radar for monitoring of mass flows – 38296

Partner(s) owning the result:

- Graz University of Technology, Inst. fÃijr Breitbandkommunikation – Helmut Schreiber

Category: A – results usable outside the consortium

Contact person for the result:

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Summary:

A new pulse-Doppler radar has been built for the SATSIE project by the Institute of Communication and Wave Propagation (now Institute of Broadband Communications) of Graz University of Technology. This instrument is based on former avalanche radars of the same institute (first developments go back to 1987) but with an updated design. The goal of this instrument is to allow a remote measurement of both position and velocity of snow avalanches (and other mass flows). By using short radar-pulses (down to a length of 1/6 microseconds) the avalanche slope can be spatially divided into up to 100 range gates with a length of 25 m each. In each of these range gates the velocity of target objects inside (e.g. an avalanche) is determined by using the Doppler effect with a typical resolution of less than 1 m/s. This velocity is measured in all range gates simultaneously up to 10 times per second. An offline software to evaluate and process the measured velocity spectra is also part of the whole radar system. That makes the radar an important tool for research by providing measured data of an avalanche against which computer simulation models can be compared, thus helping in the improvement of those models. Another application is the verification of success of artificial triggering of avalanches in order to insure safety of roads or railways. Since this triggering may happen during the night or under bad weather conditions, visual or other kinds of verification might be quite difficult. The radar is able to accomplish the detection of snow movement at distances of up to 3.5 km even under heavy snowfall since the used frequency (C-Band) is scarcely attenuated. Continuous surveillance of dangerous avalanche slopes with automatic alarm generation would be another possible application. Furthermore the radar does remote sensing and can therefore be installed at a safe location (near the bottom of the avalanche slope) which is easily accessible. The instrument built for SATSIE is of the most recent version series. Improvements compared to the older avalanche radars include (i) reduction of internal clutter by a revised signal generation method, (ii) faster signal processing using a more powerful processor, (iii) client-server scheme for easier remote-control of the radar and (iv) a new graphical user interface. The equipment consists of the antenna and the radar-box and is transportable. For remote control a PC (e. g. a laptop) is necessary, which is connected to the radar via local ethernet. Furthermore a 220 V power supply is necessary. The avalanche radar's further development during the SATSIE project proved the successful operation of the updated design and gave hints for minor improvements.

Subject descriptors:

* 192 – ELECTRONICS, ELECTRONIC ENGINEERING
* 280 – HAZARDS: NATURAL
* 290 – HIGH FREQUENCY TECHNOLOGY, MICROWAVES
* 560 – SENSORY SCIENCE, SENSORS, INSTRUMENTATION
* 563 – SIGNAL PROCESSING

Documents:

Documentation type :	Description of the instrument in 1st Annual Report
Details:	Description of the principle of operation and the technical data. More detailed publication planned together with first results from measurements at the Ryggfonn full-scale avalanche test site.
Status:	Public

Application sectors:

* 31 Manufacture of electrical machinery and apparatus
* 63.2 Other supporting transport activities
* 73 Research and development

Current stage of development:

Results of demonstration trials available
Other: Activity was to provide a radar system for project coordinator. Further radars of similar design are installed and in operation in Austria.

Potential offered for further dissemination and use:

Not applicable. Activity was provision of existing instrument and design for SATSIE project.

Profile of additional partner(s) for further dissemination and use:

Potential customers for Impulse Doppler Avalanche Radars.

European Summer University courses on natural hazards, 2007 cycle – Advanced course in avalanche dynamics and numerical modelling – 38564

Partner(s) owning the result:

– Norwegian Geotechnical Institute – Karstein Lied
– Icelandic Meteorological Office – Tómas Jóhannesson
– University of Leeds – Christopher Keylock
– University of Cambridge, Department of Applied Mathematics and Theoretical Physics – Jim McElwaine
– Federal Forest Office and Research Training Centre for Forests, Natural Hazards and Landscape – Lambert Rammer
– Graz University of Technology, Inst. für Breitbandkommunikation – Helmut Schreiber
– Centre National du Machinisme Agricole, du Génie Rural, des Eaux et des Forêts – Erosion torrentielle, neige et avalanches – Naaim Mohamed
– Università degli Studi di Pavia – Dipartimento di Ingegneria Idraulica e Ambientale – Massimiliano Barbolini
– Universitat de Barcelona – Emma Suriñach Cornet

Category: A – results usable outside the consortium.

Contact person for the result:

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Summary:

European Summer University 2007: Advanced course on the use of new models in avalanche hazard mapping The targeted audience consists of advanced students specialising in natural hazards issues and experienced engineers (outside academia) active in avalanche hazard mapping and consulting. Previous participation in one of the basic courses on avalanches offered by the European Summer University program or an equivalent formation will be a prerequisite for participation. The intensive course will give an overview of the present knowledge of avalanche dynamics (gained particularly during SATSIE), introduce the modern concepts of hazard mapping, discuss the new avalanche flow models and apply them to real-world problems in the surroundings of the course location, including substantial field work. The participants will be made aware of the different national guidelines and regulations concerning avalanche hazard mapping. If possible, representatives of national agencies responsible for avalanche safety will be invited to a presentation of the course results and a discussion of the prospects for harmonising the diverging standards within Europe. The course instructors will be recruited from the staff of the consortium members.

Subject descriptors:

* 129 – COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL
* 183 – EDUCATION AND TRAINING, LIFELONG LEARNING, REMOTE LEARNING
* 280 – HAZARDS: NATURAL
* 347 – LAND USE PLANNING/LANDSCAPE/LANDSCAPE ARCHITECTURE

Application sectors:

* 93 Other service activities
* 75 Public administration and defence; compulsory social security

Frequency-modulated continuous-wave radar for mass flow profiling – 38565

Partner(s) owning the result:

- Norwegian Geotechnical Institute – Karstein Lied
- Graz University of Technology, Inst. für Breitbandkommunikation – Helmut Schreiber

Category: A – results usable outside the consortium

Contact person for the result:

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Specific URL	http://www.leeds.ac.uk/satsie

Summary:

A high-performance profiling C-band radar based on the principle of continuous-wave frequency modulation has been developed jointly by the Norwegian Geotechnical Institute (NGI) and the Institute for Communication Technology and Wave Propagation (INW) of the Technical University of Graz. The purpose of this device is to measure the flow depth, the erosion rate and—by cross-correlation of the signals from a pair of radars positioned in the flow direction—vertical profiles of the internal longitudinal flow velocity. Its outstanding features are (i) high spatial resolution (< 0.15 m), (ii) high temporal resolution (> 100 profiles/s), (iii) narrow beam width in the flow direction, allowing to place the radars as close as 2 m without cross-talk, (iv) a detection range > 15 m, and (v) rugged construction withstanding unattended operation during an entire winter season in a cavern inside an large avalanche track. Further development has the objective of simplifying the device (at the expense of a reduced measurement rate) to the point where it can be manufactured as a low-cost snow-cover monitoring sensor. The intended use is primarily in inaccessible release zones of avalanches that endanger settlements or traffic routes. From the evolution of the snow cover depth, safety responsibles obtain decisive information on the likelihood of an avalanche release and can more securely and accurately time evacuation decisions. Under suitable circumstances (single release zone, long avalanche path, short endangered segment of traffic route), such radar systems may also be used for triggering a traffic light closing the segment as soon as an avalanche is released. Where avalanches are released artificially under storm conditions, the FMCW radars can also be used to verify whether the snow mass was indeed released, even when it does not arrive on the valley floor. NGI has an agreement with an electronics company that will produce and market such radars after positive test results from the research system at the Ryggfonn test site and the construction of a prototype of the simplified system.

Subject descriptors:

* 192 - ELECTRONICS, ELECTRONIC ENGINEERING
* 560 - SENSORY SCIENCE, SENSORS, INSTRUMENTATION
* 563 - SIGNAL PROCESSING
* 635 - TRANSPORT SAFETY/SECURITY
* 669 - WATER: HYDROLOGY

Documents:

Documentation type: Description in 2nd Annual Report of SATSIE
Details: Principle of operation. More detailed publication planned together with first results from measurements at Ryggfonn full-scale avalanche test site.
Status: Public

Application sectors:

* 31 Manufacture of electrical machinery and apparatus
* 32 Manufacture of radio, television and communication
* 63.2 Other supporting transport activities
* 73 Research and development

Current stage of development:

Prototype/demonstrator available for testing
Other: Design studies for commercial alarm device

Further collaboration, dissemination and use of the result:

MKT Marketing agreement
MAN Manufacturing agreement
FIN Development financing
CONS Available for consultancy
R&D Further research or development
Details FMCW radar functional for research purposes. Need development of a "down-graded", cheaper version for use in avalanche alarm systems, etc. NGI has an agreement with a commercial electronics company, Scanmatic, that they will produce and market a simplified FMCW radar for avalanche hazard warning. The results from the measurements in Ryggfonn are being awaited, and NGI is to construct a simplified prototype before production plans are finalised.

Potential offered for further dissemination and use:

NGI has extensive experience in all areas of snow avalanche research and hazard management. Through its close contacts to potential end-users of FMCW radar (road authorities, communal safety services, etc.), NGI knows their needs quite well and can help them in selecting the most effective mitigative measures. There is also substantial experience with georadar and its applications, and with the design and use of measurement equipment under very harsh environmental conditions, both in the mountains and off-shore. The relatively low cost of the FMCW radar system developed by NGI (with a substantial contribution from INW) will make it possible to install these devices near endangered sectors of traffic routes or in avalanche release zones, respectively. They allow monitoring of snow cover build-up and—to some degree—snow cover texture. This is important information for avalanche warning services who have to take the decision when to close a traffic route or to evacuate inhabitants of endangered settlements. The new FMCW radar systems can be used in a much wider range of situations than hitherto, opening up a small but expanding and durable market for such systems.

Profile of additional partner(s) for further dissemination and use:

For the marketing of a simplified version of the FMCW radar, a company able to efficiently produce relatively small series of devices at a high quality level is required. In addition, the company has to have experience in the design of equipment that can withstand very harsh environmental conditions. Flexibility is needed to adapt rapidly to special requests from customers.

D2FRAM – Dynamical Two-Flow-Regime Avalanche Model

Partner(s) owning the result:

- Norwegian Geotechnical Institute – Karstein Lied

Category: B – results usable exclusively within the consortium

Contact person for the result:

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URL	http://www.ngi.no
Specific URL	http://www.leeds.ac.uk/satsie

Summary: D2FRAM is a dynamical model for calculating the flow of a snow avalanche over a mountain slope, starting from user-specified initial conditions. The particular feature that sets it apart from other models for the same purpose is its ability to model flow-regime transitions from a dense to a fluidised flow regime (and back), in function of the internal state of the flowing material. In this way, D2FRAM allows much more realistic modelling of the behaviour of dry-snow avalanches. Recent measurements at full-scale avalanche test sites have produced evidence for a fairly dilute, fast avalanche head followed by a much denser and slower body. This avalanche structure may have a pronounced effect on the pressure distribution in the run-out zone, which determines the hazard zoning and land-use planning. The model may be considered an extension of the well-known Norem-Irgens-Schieldrop (NIS) model in that it uses very similar rheological relations between the stress and deformation rate for a given fixed density. However, if the dispersive pressure generated by particle collisions under shear exceeds the overburden weight, the flowing material expands until a new equilibrium between the stresses is reached. The increased flow height leads to a higher mean velocity in the fluidised parts of the avalanche. The density dependence of the model parameters needs to be prescribed; the present solution relies on theoretical and numerical studies in two dimensions as no direct measurements are available. However, different density dependence can easily be implemented in D2FRAM. If density is variable, an evolution equation must be supplied for it. Two possibilities are available in D2FRAM: (i) The density is assumed to relax from its present local value to the present local equilibrium value, which in turn is determined by the present local shear rate and the density dependence of the model parameters. The relaxation constant has to be chosen heuristically. (ii) The hydrostatic pressure distribution is abandoned and a momentum equation solved for the bed-normal component of linear momentum. In conjunction with the so-called kinematic boundary condition and the assumed profile functions of the dynamical fields, a fully dynamical density evolution equation is obtained. D2FRAM also goes beyond present models in the way it accounts for terrain-curvature effects. Curvature radii have to be significantly larger than the flow depth for the shallow-water approximation to be valid, but need not be larger than the flow width or length as in other models that do not completely neglect terrain curvature. To this end, the governing equations are formulated in a curvilinear coordinate system, using covariant derivatives instead of ordinary partial derivatives. Despite these added terms, the conservative formulation is retained so that the model can be implemented in a shock-capturing scheme. Development of the model is ongoing. The numerical implementation is first made in one spatial dimension and then extended to two dimensions. A shock-capturing, higher-order non-oscillatory central scheme is being used. It is expected that D2FRAM will undergo extensive validation in early 2007. D2FRAM will be available to the partners in the SATSIE consortium. Decisions on possible distribution beyond that circle will be taken only after validation has been successfully completed.

Subject descriptors:

* 43 - APPLIED PHYSICS
* 128 - COMPUTATIONAL PHYSICS
* 129 - COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL
* 173 - EARTH SCIENCE, EARTH OBSERVATION/STRATIGRAPHY/SEDIMENTARY PROCESSES
* 280 - HAZARDS: NATURAL

Documents:

Documentation type:	NGI Report on the physics and governing equations of D2FRAM
Details:	D. Issler, P. Gauer, A. S. Moe and F. Irgens, 2006. Flow-regime transitions in granular gravity mass flows – An extension of the Norem-Irgens-Schieldrop model. NGI Report 20021048-13. Norwegian Geotechnical Institute, Oslo, Norway.
Status:	Public

Documentation type:	NGI Report on the treatment of terrain curvature in gravity mass flow models
Details:	D. Issler, 2006. Curvature effects in depth-averaged flow models on arbitrary topography. NGI Report 20021048-14. Norwegian Geotechnical Institute, Oslo, Norway.
Status:	Public

Application sectors:

* 45 Construction
* 75 Public administration and defence; compulsory social security
* 63.2 Other supporting transport activities
* 73 Research and development

Current stage of development:

Mathematical model specified, numerical implementation in progress Prototype/demonstrator available for testing
Other: Design studies for commercial alarm device

Further collaboration, dissemination and use of the result:

CONS	Available for consultancy
INFO	Information exchange/Training R&D
R&D	Further research or development
Details	The model will be used by NGI in their consulting work on snow avalanches, primarily for hazard mapping/zoning in Norway and in the design of protective dams. Help from the consortium partners in the validation of the model will be welcome. If the model is made available to users outside the consortium at a later stage, their feedback will help the further development of D2FRAM.

Potential offered for further dissemination and use:

Profile of additional partner(s) for further dissemination and use:

Chapter 5

Project Summary

Contract no.	EVG1–CT2002–000590	Project Duration:	01/10/2002 – 31/05/2006
Title	SATSIE – Avalanche Studies and Model Validation in Europe		

Objectives:
Acquire a deeper understanding of the physical processes in snow avalanches through experiments at reduced and full scale and subsequently improve the tools for hazard mapping of snow avalanches and the design of protective measures by

- developing novel instruments and data analysis techniques for probing the structure of avalanche flows;
- carrying out experiments designed to measure the rheological behaviour of granular flows and snow at the laboratory scale, and of snow at full scale;
- studying the mechanisms of snow entrainment and deposition;
- investigating the behaviour of laboratory flows impacting on obstacles and comparing the results to measurements at full scale;
- developing new dynamical flow models for hazard mapping that take into account new insight into the structure and rheological behaviour of avalanches;
- issuing a Handbook of Dam Design that summarises state-of-the-art knowledge and best practices;
- developing reduced-cost radar systems for use in monitoring and alarm systems;
- making the results from the project accessible to avalanche professionals through publications and a European Summer University course.

Scientific achievements:

- Fluidised head with density below 100 $kg\,m^{-3}$ and length 10–100 m observed in most dry-snow avalanches in Ryggfonn. Density increases and velocity decreases with distance from head. Similar flow transitions seen in granular chute experiments but not in snow chute measurements. Velocity profile (linear vs. curved) appears to depend sensitively on the flow conditions. Novel results on powder-snow avalanche formation and behaviour from laboratory experiments.
- Direct observation of erosion processes in granular chute flows, indirect observations from Ryggfonn (abrasion in dry-snow avalanches, ploughing in wet-snow avalanches).
- Very high impact pressures observed in slow flowing humid avalanche in Ryggfonn highlight role of snow cohesion and may necessitate reevaluation of hazard from wet-snow avalanches.
- Insight from experiments was directly used in specifying the rheology and the entrainment rate in novel numerical flow models.

- Seismic signals usable for velocity measurements; can be interpreted with regard to avalanche size and flow regime in favourable situations.
- Novel or improved sensors (opto-electronic, radar, multi-directional air-pressure sensors for powder-snow avalanches) and corresponding data analysis techniques were developed and may be applicable to other phenomena as well.
- Comprehensive experiments and theoretical investigation of shock formation in avalanche–dam interactions led to improved criteria for dam dimensioning. However, some further work is needed to determine the limits of applicability of the new theory.

Main deliverables:

- *FMCW profiling radar and range-gating Doppler radar* that can be used in monitoring or alarm systems.
- *Handbook on dam design* (draft version) summarising the present state of knowledge and best practices in the choice of defense strategy against avalanches, and the planning and dimensioning of dams.
- *New numerical models of avalanche flow* for application in hazard mapping and dam design. MN2L from ETNA is already being used by professionals, D2FRAM from NGI is in an advanced stage of development.
- *Introductory and advanced course on avalanche hazard mapping, modelling and mitigation.* Training for students and professionals offered in the framework of the European Summer University in 2004 and 2007 (in preparation).
- *Summary reports* on new sensors and data analysis techniques, experimental facilities for avalanche studies in Europe, inferences from laboratory and full-scale experiments, and on impact studies.

Socio-economic relevance and policy implications:

- New numerical models contribute to more accurate hazard maps and thus to higher degree of safety and improved land use in mountain communities.
- Handbook on dam design will help to spread best practices and to obtain higher degree of safety at lower costs.
- Newly developed radar systems have moderate potential for commercialisation.
- The high degree of collaboration in SATSIE paves the ground for continued collaboration, better use of research resources, and for future harmonisation of hazard mapping regulations.
- Some of the project results may be applied to other gravity mass flow hazards (debris flows, rock avalanches), the new data analysis techniques even beyond that field.
- The project results benefit some of the economically least favoured communities in Europe.

Dissemination of results:

- Introductory and advanced course on avalanche hazard mapping, modelling and mitigation, European Summer University 2004 and 2007.
- Handbook on dam design, available from the consortium partners (in preparation).
- Numerical models available on request from Cemagref–ETNA and NGI.
- Scientific publications in peer-reviewed journals; several project reports available at SATSIE website.

Keywords: Snow avalanches, hazard mapping, hazard mitigation, dams, monitoring, alarm systems, radar, seismic signals, data analysis, image analysis, flow regimes, fluidisation, erosion, granular flows, chute flows, numerical modelling, large facilities.

Chapter 6

Project Overview

6.1 Background

Snow avalanches are gravity mass flows that occur only in mountainous terrain of sufficient inclination and at altitudes sufficient for a snowpack to form and remain for extended periods, i. e., at least several weeks. For this reason, their occurrence is more spatially restricted than for other hydrogeological hazards such as debris flows and floods, and it is more temporally limited than for rock avalanches and landslides. However, essentially all mountain slopes steeper than about 30° and receiving sufficient snow precipitation—which are truly abundant in, say, the Alps—are potentially avalanche-prone. Over an extended area, snow avalanches are a *very* frequent phenomenon, even though a given avalanche path may only rarely experience significant events that threaten human lives or goods.

While the overall risk from snow avalanches is considerably less than from landslides or floods, it still is considerable, as the most recent catastrophic winter 1999 in the Alps clearly proved, with total loss of human life approaching 100 and total damage close to 1 billion Euros. Furthermore, there are several aspects peculiar to snow avalanches that increase their importance beyond what one might think at first thought. First of all, the number of potential avalanche paths is enormous, and in most areas in the Alps (as well as in the mountainous parts of Norway or Iceland) it is impossible to build traffic routes that are not endangered by avalanches without resorting to extremely expensive measures such as many long tunnels. The main routes through the Alps have always been traffic bottlenecks, and closures due to natural hazards have significant economic consequences. A related consequence concerns settlements: Many mountain villages have very little space that is completely safe from avalanches. In earlier centuries, the alpine population was used to accept a fairly high risk, but they do not accept it any longer, nor do the tourists on which these communities are almost completely dependent economically. Thus long-term sustainability of human settlement in alpine regions is contingent upon a satisfactory reduction and management of the risk from snow avalanches (in conjunction with other natural hazards, of course).

Much applied research work is currently being expended on developing techniques and decision tools for multi-risk management. An important issue in that framework is the assessment of the relative risk from different types of hazards as well as from different modes of land-use and activities. To this end, a multitude of factors contributing to the risk should be evaluated at least approximately. With regard to snow avalanches, the main factors relevant to the risk for settlements and traffic routes are (i) the release probability per year of an avalanche of given size in a given path, (ii) the pressure distribution of that avalanche in its runout zone, (iii) the susceptibility to damage of buildings in that zone or the vulnerability of persons at those locations, and (iv) the number and value of buildings exposed to avalanches and/or the number of persons likely to be present when an avalanche occurs. But then, considering that the overwhelming majority of avalanche victims in “normal” winters are off-piste skiers and snowboarders or backcountry tourists, a different set of factors should be evaluated by avalanche forecasters and mountain

guides: (v) What is the probability of a given slope releasing within a determined, short time span (typically a few hours from now)? Road services or safety responsibles of a railway line will additionally ask about (vi) the probability of a released avalanche from a given path to reach the exposed traffic route.

As one analyses these questions with regard to the type of knowledge necessary to answer them, one finds the following research themes:

a) Question (v) is the only one to require detailed understanding of the release mechanism and data on the actual state of the snowcover at small scales.

b) Question (i) requires good data on the extreme-value statistics for the regional snow climate, qualitative understanding of the influence of the orography at the (avalanche) basin scale on snowdrift and of exposition/altitude on release probability, and finally fairly detailed understanding of the way small-to-medium-scale topographic features determine the extent of the release area for various typical snowcover structures. Some of this knowledge is also important for problem (v).

c) Avalanche (flow) dynamics is the key to questions (ii) and (vi) and also plays a role in problem (iii). While the avalanche release itself is seen as an essentially stochastic phenomenon, the ensuing flow may be amenable to deterministic modelling if the many intricate processes that may play a role are properly understood[1].

d) The answer to (iv) relies on input from avalanche dynamics regarding the vertical distribution of the loads and the impact duration. For buildings, an analysis of their response to various types of dynamic loads is in principle required (but usually replaced by empirical damage scales). The vulnerability of persons can probably only be evaluated from victim statistics.

Despite the best efforts of a large number of researchers over a period of 70 years and the enormous progress made thereby, our knowledge of all four topics a) to d) just mentioned is still incomplete in important respects. Clearly, for a decisive improvement of over-all avalanche safety all four research themes should be addressed.

It is evident, however, that different approaches are needed for the different research themes. The determination of the initial conditions in research theme b) is largely a question of climatology and requires long and reliable time series of precipitation data for statistical analysis. If the data are made available, a small group can carry out the analysis work. Estimating and eventually reducing the exposure factor in the risk equation, required for research themes d) and to some degree a), falls mostly into the realm of human geography and applied psychology. In contrast, a combined experimental and theoretical approach in the tradition of physics and engineering research is called for to address the major parts of research themes a) and c).

Among these research themes, avalanche dynamics is the one for which research collaboration at the European level is most important. Experiments play a central role here, and they should be carried out at different scales: Laboratory experiments can be controlled and repeated, but it is tricky to carry them out with snow and there are difficult scaling issues involved. Full-scale experiments, in contrast, are not fraught with scaling problems but cannot be repeated under controlled conditions and require an enormous (financial) effort. A large variety of sensors have been developed to study the internal dynamics of avalanching snow, but experience shows that many measurements need to be combined for conclusive results. Equipping and running a state-of-the-art avalanche test site exceeds the resources of a single research institute.

The reason why expectations and demands on hazard mapping tools from politicians and the public are very high, at times even exaggerated, can perhaps be explained in the following way: The destructive forces of medium to large avalanches are far too large to be absorbed by buildings except at the end of the runout zone. Therefore, well informed land-use planning is necessary to avoid construction in

[1] Alternatively, one may opt for treating the flow by statistical methods as well. The two main disadvantages of the statistical approach are the difficulty of adapting the statistical model to a different region for which there are few reliable avalanche observations and the lack of information on the pressure distribution in the runout zone, especially in complex situations.

endangered areas. The scarcity of good construction ground places a high premium on accurate hazard mapping. However, even if avalanche science had perfect control over the many factors that influence avalanche flow, the inherently stochastic nature of the weather precludes precise determination of the initial conditions and thus calculation of runout distances and pressure distributions at the level of metres. Nevertheless, the goal must be to attain a thorough understanding of the processes and to develop simulation tools that yield credible results even in complex or unusual situations.

In certain cases, technical protection measures may be a sensible way of increasing public safety in certain areas. But both measures that prevent avalanche formation (steel bridges and nets in the starting zone) and dams that stop or deflect avalanches in the runout zone do not provide complete safety, and their effectiveness depends on many poorly understood factors. As a consequence, a large safety margin should be applied in their design, making them often much more costly. As an example, the cost of a dam scales with its volume, which in turn scales with the square of its height.

When SATSIE was planned and the decision had been taken to concentrate on avalanche dynamics, as opposed to the other research themes outlined above, the following open questions were felt to be most pressing in view of reliable hazard mapping and rational design of passive protection measures such as dams and braking mounds:

1. Which flow regimes occur in avalanches, under which conditions are they attained, and how does avalanche motion depend on the flow regime?
2. Specifically, in which way and how quickly do powder-snow avalanches form from originally dense-flow avalanches?
3. Which factors determine the rate of snow erosion from the bed and deposition onto it, what are the mechanisms, and how does entrainment influence avalanche movement?
4. How can avalanche impact on an obstacle be modelled, and which conclusions can be drawn for the design of effective protection measures?

These are fundamental questions of avalanche dynamics for which no sufficiently comprehensive answers have been found in the past to form a sound basis for developping the highly accurate models that are demanded by the authorities and the concerned public. Tackling these problems and finding partial if not complete answers to them will lead to a high degree of innovation not only in avalanche science but also in related disciplines, in particular the study and mitigation of other gravity mass flow hazards such as debris flows and rock avalanches.

6.2 Scientific/technological and socio-economic objectives

As discussed in the preceding section, the primordial goal of SATSIE was to contribute to avalanche safety of settlements and traffic routes by creating improved tools for hazard mapping and designing protection dams. From the full spectrum of active and passive avalanche protection measures, these are the ones that require progress in avalanche dynamics to be made and benefit strongly from a project co-ordinated at the European level. Four central scientific questions were identified, which can be approached and brought to bear on the central goal by working towards a number of well defined main objectives. These main objectives also form logical steps that defined the temporal order of the work to some degree, as will be seen below.

Main objective #1: Sensors for avalanche experiments.
Objective 1 is a prerequisite for achieving Objective 2. Planned new developments include powerful yet low-cost Doppler and frequency-modulation radar systems for use both in experiments and in avalanche alarm systems to obtain information about the pressure and velocity distribution in the avalanche. Existing techniques such as a concentric-cylinder rheometer, paired LED sensor arrays for velocity profile measurements and load plates measuring normal and tangential stresses at the ground will be optimised and adapted to the forces, velocities and environmental conditions of large snow avalanches. Improved analysis techniques will be developed for the data from radars, load cells sensitive to high-frequency particle impacts, and geophones. These sensors will be installed at NGI's test site Ryggfonn in Grasdalen, western Norway, so that comprehensive and detailed data pertaining to Objective 2 may be obtained.

Main objective #2: Laboratory and full-scale avalanche experiments.
The envisaged experiments need to probe the internal dynamics of avalanches by simultaneously measuring stresses, velocity profiles, fluctuating internal motions and snow entrainment rates at different locations along the path, besides the traditionally measured variables. The laboratory experiments in chutes of various sizes with both dry granular materials and snow, serve to study the flow dynamics under controlled conditions, systematically varying the key flow parameters. In the full-scale experiments, care will be taken to also determine the relevant snow properties so that the measurements can be compared with the laboratory results and the scaling behaviour of various processes determined. The Ryggfonn full-size test site will be specially equipped for studying the interaction of real snow avalanches with a retaining dam, in order to compare the data with laboratory experiments and model predictions obtained in the EU project CADZIE.

Main objective #3: Model development. Using the data from the experiments (Objective 2), the three main shortcomings of presently used models will be addressed, namely (i) the lack of realistic rheological laws, (ii) the absence of snow entrainment in the modelling, and (iii) the heuristic description of the formation of a layer of suspended particles (the powder snow "cloud"). Mathematical expressions will be sought for the internal stresses, the entrainment and the suspension rates that capture the essential physics of the phenomena and depend on local flow variables (e. g., the shear rate and the flow depth) and the measurable material parameters of the snow (density, shear strength, cohesion).

Main objective #4: Dissemination of results. A handbook summarising the results of modelling studies and full-scale measurements at retaining and deflecting dams and the recommended procedures for engineering such dams will be made widely available to avalanche professionals and safety officials for mountain areas. Practical application of the new avalanche flow models will be facilitated through users' manuals enriched with realistic examples. At the end of the project, the new tools will be introduced to avalanche professionals through an intensive course in the framework of the well-established European Summer University on Natural Hazards, to be held jointly by representatives of the partner institutions.

The general structure of the project closely followed these four main objectives, with Work Packages 1 (Sensor development) and 2 (Data analysis techniques) responding to Main objective #1, Work Packages 3 (Instrumentation of selected facilities) and 4 (Measurement campaigns) to Main objective #2. Work Packages 5 (Model development) and 6 (Data sharing and dissemination of results) directly corresponded to Main objectives #3 and 4, respectively. Each Work Package was broken down into tasks that comprised more narrowly defined activities, almost completely enumerated in the description of the Main objectives given above.

Socio-economic objectives were addressed to some degree in Main objective #4 and Work Package 6 in that many project deliverables were defined with the end-users in mind. The main benefit of the project for society, and particularly for mountain communities threatened by avalanches will be realised indirectly when the end-users (mainly the authorities at different levels and in some countries avalanche experts from SMEs active in hazard mapping and the design of protection measures) apply the new tools produced by SATSIE to create more accurate hazard maps and design more effective and less costly protection dams.

It should also be mentioned that the radar systems that were developed in response to Main objective #1 can be used—directly or after some further development towards commercialisation—in avalanche monitoring and alarm systems. This creates modest business opportunities for a SME in the field of manufacture of electronic and communication devices and for a number of SMEs experienced in the planning and deployment of monitoring and alarm systems in mountain environments. Such systems need not be limited to snow avalanches but may also be effective for other gravity mass movements, mainly debris flows or rock avalanches.

6.3 Applied methodology, scientific achievements and main deliverables

6.3.1 Remarks on the methodology

As shown in the preceding sections, much basic scientific research had to be carried out in SATSIE in order to achieve the practical goals and objectives. The open questions targeted for research are problems of avalanche dynamics, which can be considered a special branch of continuum or granular mechanics. Accordingly, the classic approach of physics and the other natural sciences—a continuous interplay of experimental and theoretical work—was considered the most adequate approach. In contrast to fundamental physics research, the ultimate goal could not be to find a stunningly beautiful and simple equation that would describe all of avalanche dynamics, but to develop one or several mathematical models that capture enough of the complex phenomenon to allow reasonably accurate predictions in as large a palette of situations as possible.

It was seen early in the preparation phase of the project that innovative new measurement and data analysis techniques were needed in order to probe the internal dynamics of avalanches, as opposed to the traditionally measured external variables such as the front velocity and the run-out distance. For this reason, the development of new instruments assumed an important role in the project. It was also clear that these developments should be givenhigh priority in the beginning stage of SATSIE so that the new instruments could be used as early as possible.

Snow is a complex, highly variable material. In contrast to dry granular materials of macroscopic particles, cohesion forces are undoubtedly important at low shear rates. Under low shear, snow thus exhibits properties of a cohesive non-Newtonian fluid, with significant shear thinning as the shear rate is increased. Under suitable conditions, the avalanche flow may become quite similar to a dry granular flow, however. To the intrinsic complexity of granular flows, snow avalanches add further properties which introduce additional scales into the problem. For this reason, the scaling behaviour of avalanche flows is not easily controlled by simple theoretical arguments. Experiments should ideally be carried out at a variety of scales in order to understand the scaling issues and achieve reliable extrapolation of the results to the scale of natural avalanches. However, laboratory (chute) experiments and full-scale measurements are often complementary: Detailed measurements under controlled, repeatable but somewhat unrealistic conditions are possible in the laboratory while it is difficult to foresee the timing and characteristics of avalanche events in a test site, and detailed measurements of internal properties of large avalanches are difficult, sometimes dangerous and always expensive.

SATSIE responded to this fundamental difficulty by pooling the resources of most European avalanche research institutes, concentrating on only one test site (Ryggfonn) that was already equipped to some degree and adding the types of sensors that promised the most comprehensive insight at reasonable cost. Furthermore, several series of dedicated chute experiments were started at Alpe d'Huez / Col du Lac Blanc and Pavia, and continued at Bristol and Reykjavík. The goal of these experiments was to study specific aspects of the dynamics in great detail, particularly the flow regime and rheology through the velocity (and density) profiles, entrainment mechanisms and impacts onto obstacles like masts, catching and deflecting dams. It was not feasible to repeat these experiments at much larger scales, but at least it was possible to infer the density and velocity distribution in full-size avalanches from pressure measurements, geophone and radar data. (Much better information, also pertaining to erosion and entrainment, was expected to come from the new FMCW radars, but technical difficulties prevented this.) Under favourable conditions at Ryggfonn, one could also hope to obtain valuable data on impact pressures, overrun velocities and similar variables from measurements and observations at the dam.

Extensive discussions among the modellers in the SATSIE team early in the course of the project showed that there was little hope to combine all the envisaged innovations into a single model. Instead, we would try to construct two models that address different aspects of the complex rheological behaviour of snow avalanches: In an approach that could be termed empirical, the ETNA team would modify their

existing model of mixed avalanches so that the friction law would reflect their findings from the snow chute at Col du Lac Blanc; in addition, a physically founded entrainment/deposition model would also be integrated tightly into that code. The development at NGI would instead emphasise the observed property of dry-snow avalanches to attain a more dilute, fluidised flow regime. In the dispersive stresses, which are a fundamental property of the NIS model developed at NGI fifteen years earlier, there slumbers the potential of describing such transitions in a simple yet convincing way. After SATSIE, when sufficient experience has been collected with both types of models and perhaps more illuminating experimental data have been collected, a new model combining the best properties of both these models may perhaps be constructed.

6.3.2 Scientific results

In this section, we summarise the results of the entire project, pointing out the interconnections with other project task or activities, and compare them to the established knowledge before SATSIE and to the level of insight that we believe to be needed to fully attain the ultimate goals of SATSIE.

Sensors and data analysis techniques

Before the start of SATSIE, a wide variety of sensor types that could be used in full-scale avalanche measurements or in chute experiments and corresponding analysis techniques had already been developed; a brief overview can be found, e. g., in (Issler, 2003).

In order to study the impact of avalanches on the Ryggfonn dam, it was decided to install *3D load plates*, capable of measuring the two tangential and the normal components of the load) on the upstream dam side. In order to link the impact forces to the properties of the avalanche, the load plates should be supplemented with a device that measures the flow depth and the velocity profile across the depth of the flow. A simple technique are optoelectronic devices, to be discussed below. An alternative is to bury pairs of profiling radars (Gubler and Hiller, 1984) in the path at suitable locations. Using frequency sweeping at a fixed rate and comparing the frequency spectrum of the received signal to the currently emitted frequency, the relative strength of the echos from different distances can be determined. In this way, a profile of the radar echo strength across the flow depth is obtained. By cross-correlating the signal from a chosen distance with the corresponding signal from another radar a small distance further downstream, the velocity of snow clods at this height can be evaluated. Repeating this procedure for different heights in the flow, a velocity profile is obtained.

The **3D load plates** were built by somewhat modifying a design that has been used several times in Austria by AIATR. Construction and installation were rapid, and the load plates have worked flawlessly since the winter 2002/2003 (see First Annual Report and Deliverable D10, Documentation of instrumentation scheme and installation work at the selected sites). Surprisingly, the measured loads were significantly lower than expected in many cases, but it was eventually understood that this is not due to faults in the sensor system.

Frequency-modulated continuous-wave (FMCW) radar has been used by SLF for more than two decades, first at the Val Medel test site and later at the Vallée de la Sionne site (see Deliverable D8, *Updated report on European avalanche test sites*, for more details). They not only provided information on flow depths and erosion rates, but also on the structure of the flow (Issler, 2003; Gauer and Issler, 2004) and yielded perhaps the first velocity profile from a full-scale avalanche (Gubler et al., 1986). The two main limitations of SLF's old system are the sweeping frequency that leads to fairly large errors in the velocity determination, and the wide opening angle of the antenna that prevents the radars from being placed closer than 5–10 m and so makes it difficult to obtain good cross-correlations. NGI proposed to exploit advances in microwave technology to raise the sweeping frequency from about 40 Hz to 100 Hz and to use antenna arrays that produce a narrow beam in the flow direction. In this way, the radars can

be placed as close as 2 m apart and Doppler broadening due to the opening angle of the beam is strongly reduced.

The development of the new radar turned out to be much slower and more difficult than anticipated. Deployment of the prototype at Ryggfonn was delayed by one season because of a severe illness in the family of the developer at NGI and unusable printed circuit boards delivered by a supplier. When the four systems were assembled, they performed to expectations in the laboratory tests. However, when installed in caverns in the soil at Ryggfonn during the winter 2004/2005, their output power deteriorated rapidly to the point where no analysable signal was obtained from avalanches passing over them. A series of improvements, including much better corrosion protection of the electronics, could not prevent the same symptoms from reoccurring in the winter 2005/2006. Absorption of water by the antennas was suspected to be the reason and new antennas made from different materials less susceptible to water absorption were installed during the winter (thanks to abnormally low snow quantities at Ryggfonn), but to no avail. The entire design will be scrutinised for possible susceptibility to low temperatures and humidity.

The successful tests of the FMCW radar in the laboratory show that the concept is sound and that the instrument will be very powerful once it has successfully been adapted to harsh environmental conditions. As it stands, it is an instrument primarily for research, designed for high data rates and high resolution. FMCW radar has been used for monitoring the snow cover evolution in starting zones and triggering an alarm if the snow depth changes suddenly, indicating release of an avalanche. For this purpose, a downgraded, cheaper version of the NGI radar would be ideal. As soon as the radars installed in Ryggfonn have worked flawlessly for an entire winter season, development of a commercial version will be started in collaboration with a SME that will take over manufacture, marketing and servicing.

The situation in Ryggfonn, available expertise within the collaboration and budgetary constraints suggested that an improved **range-gating Doppler radar** should be installed to follow the velocity evolution of the avalanches along the path. Over the past fifteen years, INW has developed several generations of such portable radar systems that have proven their performance at the Vallée de la Sionne test site, among others. The availability of improved electronics components and of significantly more powerful controllers suggested that a more powerful system could be built at lower cost than hitherto. In order to stay within budget, the 35 GHz part, intended for the study of the powder-snow cloud, was omitted; recent experience from Vallée de la Sionne had shown that it is of limited value because large particles carried in the fluidised layer at high velocity completely dominate the signal even in the Ka-band. The C-band radar was completed on budget and installed at Ryggfonn. It boasts up to 100 range gates with a minimum length of 25 m and a significantly improved measurement frequency (up to 10 complete spectra per second for each range gate). Comparison of Ryggfonn data from AIATR's previous generation radar and the new one clearly showed that the improvements significantly enhance the precision of, e. g., accelerations derived from the time evolution of the velocity measurements. The enhanced spatial resolution is also crucial in the interpretation of the data. The new Doppler radar thus is a research instrument of highest value. Thanks to its reduced cost, it may also become an alternative to the cheaper continuous-wave Doppler radar in the monitoring of avalanche paths that cross traffic routes if it is advantageous to obtain spatial information on the avalanches.

Each **optoelectronic sensor** consists of a light-emitting diode (LED) and a photoresistor mounted next to each other so that the photoresistor measures the light that is emitted by the diode and then reflected by passing snow particles. The particulate structure of the flow leads to characteristic fluctuations of the signal intensity, which can be exploited to infer the particle velocity by cross-correlation with the signal from another optoelectronic sensor further downstream. Suitable distances are a few centimetres for chute flows and a few decimetres for natural avalanches. Assembling many sensor pairs in a vertical array, the velocity profile may be measured. This type of sensor is very well suited for measurements in chute flows. A prerequisite for applying the method to natural avalanches, however, is to have a slender, preferably wedge-like instrument support constructed in the flow path, on which the sensors can be installed.

SATSIE brought two main developments to this sensor type. The first concerned miniaturisation for measuring the velocity profile very close to the bed in chute flows at Col du Lac Blanc. In this way, the ETNA group was able to show that—contrary to what their earlier, less resolved measurements had suggested—no slip occurred at the bed–flow interface if the bed was sufficiently rough, but the mean shear rate in the bottom layer was an order of magnitude larger than in the overriding layer. The second development is due to J. N. McElwaine (DAMTP), who carefully analysed the cross-correlation methods used hitherto to obtain velocity profiles (McElwaine and Tiefenbacher, 2003; McElwaine, 2004). He found that flow acceleration and velocity components perpendicular to the mainflow direction may produce non-negligible errors in the estimate of the mean downstream velocity. He proposed an improved sensor design that uses three vertical rows of sensors instead of only two and an analysis technique that obtains accelerations and estimates the vertical velocity component as well. In highly stationary chute flows as the ones at Col du Lac Blanc, the conventional sensor design is sufficient, but for natural avalanches or non-stationary chute experiments as the ones at SLF's chute at Weissfluhjoch/Davos, the improved design gives much more reliable results.

Direct measurements on powder-snow avalanches (PSA) are very rare. Traditionally, video filming has been used to find the front velocity and dimensions of the snow cloud whereas load cells, mechanical anemometers, Pitot tubes and Ka-band Doppler have been applied to obtain data directly from the interior, often with only moderate success. Concentrating instead on the air flow around the PSA, McElwaine (2005) found that much can be deduced about the size and velocity of a PSA by properly analysing the pressure evolution at a fixed point in or near the path of the PSA. The 20 m high tower in the Vallée de la Sionne test site would be an ideal location for measuring air pressure. However, the air-pressure sensor would have to withstand the harsh environment during the winter season, not be destroyed by the forces inside the avalanche, and to correctly measure the pressure in a flow that changes direction rapidly and radically. As no existing pressure gauge fulfils these conditions, two novel **air-pressure sensors** were designed. In the simpler design, eight orifices are distributed in an optimised way over the surface of a hemisphere about the size of a football and connected together to one side of a single differential pressure transducer. The other side of the transducer connects to a chamber at the mean ambient pressure before and after the avalanche event. Using inviscid flow theory around a hemisphere, one finds that the directional and velocity dependence of the measured pressure for given static pressure is significantly reduced from Pitot probes (McElwaine and Turnbull, 2005a). With this sensor, several mixed avalanches at Vallée de la Sionne could be successfully analysed in the winter 2003/2004.

Measuring the velocity vector and the static pressure simultaneously requires a sensor with several holes, each of which is connected to its own transducer. Based on the experience with the eight-hole transducer, McElwaine and Turnbull (2005a) proposed a five-hole five-transducer sensor, which was tested during the winter 2004/2005. No measurements were obtained because all transducers were destroyed relatively early in the winter. The likely cause was determined to be freezing inside the sensor due to poorly controlled vapour pressure gradients. Improvements in the design have been proposed, but financing was lacking and no tests could be conducted during the winter 2005/2006.

In many cases, both in full-scale tests and at the laboratory scale, **video observations** are among the easiest measurements to perform. Much research has been dedicated to the analysis of video data in many disciplines, and for many applications powerful software packages are on the market. Nevertheless, experience has shown time and again that there are many subtleties involved in obtaining good results, particularly under field conditions in avalanche research where brightness may be very high and contrast low, observation distances may be long and the avalanche may move across large viewing angles. Hence, optimised filming techniques are the first and one of the decisive steps towards successful data analysis. In a SATSIE memo, guidelines for avalanche filming have been formulated.

A software suite consisting of Matlab and C routines for determining the spatial extension of the moving body and obtaining its velocity field from video film has been created by J. N. McElwaine (see Deliverable D6, *Sensor Design and Analysis Techniques for Snow Avalanches*) and successfully applied to the existing footage from Ryggfonn and several avalanches measured by DGG in the Spanish Pyrenees.

In order to analyse even films taken without a tripod, a method was developed for stabilising the video frames.

Particle tracking on high-speed video films was the main data analysis method for the chute experiments with granular materials in Pavia. Careful adjustment of the lighting and selection of the viewframe were found to be very important for obtaining analysable videos. As described by Barbolini et al. (2005), several widely different approaches to image analysis were applied and tested against manual analysis. In this way it has been possible to select the best suited method for each particular variable (density profile, velocity profile, fluctuations. These methods were developed jointly with another project at DIIA on debris flows, and they have since been successfully applied to high-speed video data on subaqueous laboratory debris flows obtained by the University of Oslo in collaboration with the St. Anthony Falls Laboratory, University of Minnesota, Minneapolis.

Considerable progress was made over the duration of SATSIE in the **analysis of seismic signals** from snow avalanches. The new methods may also find application in other kinds of gravity mass flows (Suriñach et al., 2005) such as debris flows, which have so strong erosive power that installation of sensors in the bed is not usually an option. For a quarter century, simple geophones have been installed at Ryggfonn in the approach to the dam and at the uppermost mast, but other than for triggering the measurements of the other sensors, these data could not be used hitherto. These data were reanalysed using the Fourier transform technique in a sliding window of carefully chosen width. Vilajosana et al. (2006) found that, as the avalanche front passed over a sensor, the high-frequency components of the seismic signal increased very sharply, allowing in many cases to determine the arrival time quite precisely with the so-called picking method. Where this method gave ambiguous results, cross-correlations between adjacent sensors could be used to determine the differences in arrival times instead (all geophones are synchronised to the same time standard). Comparison with the few velocity measurements with Doppler radar (Schreiber et al., 2001; Gauer et al., 2006) showed good agreement between the different methods.

The much more sensitive 3D geophones installed at one location in the Ryggfonn path and at a distance of approx. 500 m from it allowed to obtain the phase velocity and the attenuation factor of superficial seismic waves at Ryggfonn. On the basis of this information, it was possible to determine the seismic energy released by one avalanche in the winter 2005. With reasonable assumptions on the ratio betwen the energy dissipated thermally and seismically and the avalanche velocity (from the old geophones), the avalanche mass could be estimated and was found to be in reasonable agreement with the direct observations. If this method is refined further and data from more avalanches can be analysed, it will become possible to estimate avalanche sizes in a network of seismic stations for the monitoring of avalanche activity: Triangulation would give the distance of the avalanche and hopefully also an estimate of its velocity, and from the intensity the size is deduced.

An important problem in data analysis is to detect signs of changes in the behaviour of a system that do not manifest themselves in an abrupt change of some mean value or a simple moment. Specifically, flow-regime changes in granular flows might show such behaviour in certain cases. Statistical methods based on the generation of surrogate data with the same mean and variance as the original data, but randomly varying critical exponents, and analysis with wavelet transforms have been developed recently (Keylock, 2005, 2006a,b). They are described in some detail and with examples in Sect. 3.4.2. For this reason, they will not be further discussed here.

Experiments at the laboratory and full scales: rheology and flow regimes

Under the conditions in which granular chute flow experiments are traditionally conducted, the flows are dense in the sense that the grains have enduring contacts with the neighbouring grains. Accordingly, dry friction between grains is the dominant process. It has been found (Pouliquen, 1999; Pouliquen and Forterre, 2002) that stationary flows are possible only within a limited range of slope angles that depends on the granular material. Furthermore, for a given slope angle, θ, there are limiting depths $h_{stop}(\theta)$,

below which the flow ceases, and $h_{start}(\theta)$, which is the minimum for the flow to start. Even though there is some controversy (GDR MiDi, 2004; Rajchenbach, 2004) about the correct interpretation of the measurements, it seems that the mean velocity in stationary granular flows scales as $\bar{u} \sim h^{3/2}$. This would then clearly indicate that granular avalanches deviate in significant ways from the predictions of the simple Savage–Hutter model (Savage and Hutter, 1989, 1991) that assumes Mohr–Coulomb dry friction only.

When these findings from highly idealised laboratory experiments are compared to the case of typical snow avalanches, several questions arise:

1. How can the rheology exhibited by the laboratory experiments be extrapolated to the relatively high Froude numbers in real avalanches?
2. What effect do the snow properties (wide dispersion in size, low restitution coefficient, cohesion) have on the rheology?
3. What happens in steep slopes where stationary flows are not possible?

ETNA studied the first two questions by performing **stationary chute-flow experiments with snow** instead of granular materials at their high-altitude station at **Col du Lac Blanc** / Alpe d'Huez. Any differences from the results found in earlier chute experiments should then, in principle, be due to the specific properties of the snow. Over the course of three winters, many varieties of snow could be studied. The results analysed and published so far (Bouchet et al., 2004) regard mostly fine-grained snow whose original density varied between 220 and 360 kg m^{-3}. The main findings can be summarised as follows:

- Above a bottom layer about 10 mm deep, the velocity profiles were *linear*, i. e., the shear rate $\dot{\gamma}$ was independent of the height above the bed. In the range of slope angles considered (31°–39°), it was found to be $\dot{\gamma} = (12.5 \pm 1.8)\,\mathrm{s}^{-1}$, without any apparent dependence on either the flow depth or the slope angle.
- High-resolution measurements near the bed revealed a strongly sheared bottom layer, with a shear rate about one order of magnitude larger than in the upper layer and a quite sharp transition between the layers. The depth of the bottom layer appears to grow with particle size.
- If the bottom shear layer is approximated by a slip condition, the *effective* friction coefficient can be written as
$$\mu_{\mathrm{eff.}}(h, \bar{u}) = \mu_0 + \frac{\bar{u}}{V} - h\frac{\dot{\gamma}}{2V}, \tag{6.1}$$
where $\mu_0 \approx \tan(15.6^\circ) = 0.28$ in the experiments, $\dot{\gamma}$ is the constant shear rate mentioned above, and V is a velocity scale that depends on the bed conditions. For the chute experiments, $V \approx 9.1\,\mathrm{m\,s^{-1}}$.

These results are compatible with the velocity profiles found in small snow avalanches by Dent et al. (1998) and in small laboratory flows by Rajchenbach (2003). However, they defy a traditional rheological description and in particular differ from Bagnoldian behaviour, which stipulates $\bar{u} \propto h^{3/2}$ instead of the linear behaviour found by Bouchet et al. (2004). A theoretical derivation of such behaviour has been proposed by Rajchenbach (2003). He argues that a dense granular assembly absorbs the momentum from an impacting particle in a collective way rather than through distinct binary collisions and that the restitution coefficient measured in binary collisions becomes irrelevant. It is important to note that such behaviour occurs at high densities near the dense packing limit; for well rounded snow grains, this limit should be around 500–600 kg m^{-3}. Densities could be measured only in a few runs and were in the range 300–350 kg m^{-3}, with large uncertainties but clearly below the dense packing limit.

However, the abrupt change of the shear rate at about 1 cm from the bed surface for rounded grains and at 2 cm for surface hoar grains may hold the clue for resolving this apparent discrepancy. Visual observation of the chute flows revealed the presence of snow clods ("aggregates") that probably formed

in the hopper, during transport from the hopper to the chute. They occurred in all sizes up to about 7 cm. The velocity-profile data from the optoelectronic sensors were analysed for episodes when the velocities measured by two or more vertically adjacent sensors were nearly equal (Bouchet and Naaim, 2004). These were interpreted as passage of an aggregate whose size is given by the number of sensors with equal velocity. In this way, the distribution function of aggregate sizes was determined to decay roughly with the inverse of the aggregate size. Now, according to the model proposed by Rajchenbach (2003), the shear rate scales with particle diameter d as $\dot{\gamma} \propto \sqrt{g/d}$. Applying this to the Col du Lac Blanc experiments, the shear rate should be of the order of 100–200 s^{-1} if the snow grain size is used as the particle size in this equation, but it drops to 10–15 s^{-1} when the measured aggregate sizes are assumed instead. Furthermore, large aggregates were observed near the flow surface, not near the bed. Good agreement is therefore obtained with that aspect of Rajchenbach's theory. Furthermore, if aggregates account for much of the flowing mass, the bulk density will be significantly lower than expected from the packing and the intrinsic density of ice grains (917 $kg\,m^{-3}$) because the aggregates contain many voids and have only about half the density of snow grains. The measured densities would then be compatible with dense packing.

In summary, the Col du Lac Blanc chute experiments make a strong case in support of Rajchenbach's theory of densely packed, rapid granular flows. This flow cannot be described in conventional rheological terms, but an effective friction coefficient can be determined for steady-state shear flows. That coefficient should also be applicable to transient flows not too far from steady state. The experimental results have been used in the new model MN2L (see below on page 85). Measurements of the bulk densities during the flow and of the aggregate densities immediately afterwards are desirable confirm the link to the theory.

The bulk density is admittedly difficult to measure in chute flows with snow[2]. In granular flows with uniformly sized particles, image analysis methods can be used to determine the density profile (Barbolini et al., 2005) along with the mean velocity profile, the fluctuation velocities and the flow depth. Thanks to reliable algorithms, changes in these quantities can be tracked with good temporal resolution. Such a set-up was used for the **chute experiments in Pavia**. A first series of experiments studied transient flows over smooth and rough beds. Later on, a new feeding system providing quasi-steady flows was also used, particularly when studying flow interaction with obstacles.

Observations from the widely known Japanese experiments with ping-pong balls (Nishimura et al., 1998) and the chute experiments in Pavia (Barbolini et al., 2005) in the transient mode clearly indicate that granular flows may attain another, much more dilute flow regime under certain conditions. On top of the shallow dense body of the ping-pong ball avalanches, a saltation layer of bouncing particles was clearly visible. In the Pavia chute, the particle volume concentration c decreased rapidly from the core,where $c \approx 0.4 \ldots 0.6$, to the upper surface over a layer of approx. two particle diameters. A similar density drop occurred in the bottom shear layer. Moreover, the density increased steadily over a distance of 0.3–0.5 m from very dilute at the front to 0.4 or more in the body. Similarly, it decreased again in the tail portion of the flow. This transition manifested itself in the velocity profile as well: The saltating particles in the head exhibited a uniform velocity profile whereas a curved profile was found in the body. These experiments could not determine the evolution of the saltation layer in the front because the chute is of limited length (6 m) and high-speed video recordings were taken at one location only.

Besides the density variation along the length of the flowing mass and the corresponding changes in the velocity profile, other important findings from these experiments were the following:

- The middle layer of the body of the flows was dense, but clearly below the dense packing limit. From considerations of the mean free path, one would categorise the flows as being in the collisional regime. At the head and tail, transition to the inertial flow regime occurs.
- The velocity profiles are not linear in the body of the flow. No fits have been published, but the velocity profiles are at least qualitatively compatible with the Bagnoldian shape.

[2] Capacitance sensors (Louge et al., 1997) do permit such measurements, but they remain very expensive.

- The granular temperature, T, is considerable throughout the flow. It is lowest in the middle, dense layer of the core and highest in the bottom shear layer where the fluctuation velocity, $u' \equiv (T/2)^{1/2}$, attains $u' \approx 0.1\bar{u}$. Higher granular temperatures are associated with lower densities.
- The slip velocity depends on the bed roughness and the slope angle, but these dependencies have not been studied systematically yet.

The chutes in Pavia are similar in their dimensions and inclination angle to the Col du Lac Blanc chute, but they differ strongly with regard to the granular material (snow vs. plastic beads or glass particles), the initial conditions and the measurement techniques. The strikingly different flows obtained at the two locations do not imply that there are contradictions or errors in of the experiments. Rather the lesson is (once again) that granular flows depend very sensitively on the initial and boundary conditions. It would be very interesting to repeat the snow experiments with a dry, non-clustering granular material instead and to perform transient experiments with snow under the protocol used in Pavia.

It is most interesting to compare the chute results to **observations from Ryggfonn**. Due to the failure of the FMCW radars, the only internal information from the avalanches comes from the large load plates in the lower track and on the dam, and in two cases from Doppler radar data. Thanks to careful analysis of the available data, including cross-correlation of pressure data, a reasonably consistent picture of dry-snow avalanches at Ryggfonn emerges (Gauer and Kristensen, 2005b,a; Gauer et al., 2006):

- The mean downslope velocity decreases close to linearly from the front to the tail.
- Dry-snow avalanches develop a fluidised layer at the front, whose length is typically between 30 and 100 m and whose density is up to an order of magnitude smaller at the front than in the dense body. The density probably increases steadily towards the body.
- The fluidised layer carries a certain fraction of fairly large blocks.
- The load plates in the dam often show the tangential stress to be independent of the normal one. This probably indicates gliding along a plane of shear failure, where the stress is limited by the shear strength of the snow.

At first sight, these observations are reminiscent of the granular flows at Pavia in that a similar head–body–tail structure is observed. The densities inferred for the fluidised layer would also place it squarely into the grain-inertia flow regime, although with stronger effects due to aerodynamic forces. There is no data on the velocity profile and density in the body. For this reason, no strong conclusions can be drawn as to the rheology of the dense part and the applicability of the results from the Col du Lac Blanc chute. All observations appear to be consistent with the measurements at the better equipped test site at Vallée de la Sionne, Switzerland, that have so far been published.

Experiments at the laboratory and full scales: entrainment

Reanalysis of data from Ryggfonn recently led us to the conclusion that dry-snow avalanches at Ryggfonn on average double their mass from release to runout (Issler et al., 2003). Sovilla et al. (2001) found much larger growth factors at intermediate locations along the small Monte Pizzac path in Italy, and similar numbers as in Ryggfonn were inferred at Vallée de la Sionne (Sovilla, 2004). Unfortunately, no entrainment rates could be measured at Ryggfonn during SATSIE because of the mentioned problems with the FMCW radars. On video material and during field work after successful artificial releases, grooves and impact craters could be observed that lend support to the suggestions for erosion mechanisms proposed by Gauer and Issler (2004), but quantitative analysis has not been possible.

Direct observation of the entrainment process is possible at the Pavia chute. The segment of the chute bottom at the lateral observation window was replaced by a shallow trough that was filled flush with the original chute bed, using the same material of which the flow consisted, but differently coloured. As the flow passed over this segment, the incipient motion of the entrainable material could be easily measured by the standard techniques and the entrainment rate computed. The first round of experiments

used a rather short trough; as a consequence, the steps at the ends of the trough played a significant role. Preliminary runs with a modified setup have been carried out, but not published to date. Neither are the results of these few experiments representative nor is their applicability to snow avalanches clear, but they nevertheless offer a first glimpse into the mechanics of this long neglected phenomenon. As the flow passed over the erodible portion of the bed, the bed particles began to slowly shear within a clearly limited zone, without being entrained into the flow at first. This erosion front moved with the avalanche head; its inclination depends on the flow velocity. The frontal erosion closely resembles the ploughing described by (Gauer and Issler, 2004). It could be observed how bed particles in the thinlayer at the interface between the flow and the bed were taken out of the slowly deforming bed and entrained in the flow by a sort of abrasion process. Varying the flow velocity of the non-steady flows by choosing different acceleration lengths, a linear dependence of the entrainment rate on the approach velocity was found. However, many more experiments should be carried out in order to firmly establish a quantitative relation.

Powder snow avalanche formation: laboratory experiments and theory

Contrary to what their name suggests, powder snow avalanches (PSAs) are not an independent phenomenon like, e. g., wet-snow avalanches because they always start as dense-flow avalanches. One may conjecture that suspension of fine particles mostly occurs from the fluidised head; if there is no transition to fluidised flow, the suspension rate probably is very low and no sizeable suspension flow develops. At least in the formation phase, the dense flow and the suspension flow are coupled, forming what is often called a mixed or dry-snow avalanche (terminology is not standardised in this field). If sufficiently developed, the suspension flow may separate from the dense core when the latter comes to a halt or when the suspension flow leaves a gully at a bend. Practical interest in PSAs is due to their high velocities (internally, up to $100\,\mathrm{m\,s^{-1}}$ have been measured by Doppler radar) and long run-out distances. Pressures are usually one to two orders of magnitude lower than in the dense core of the avalanche, but can still inflict enormous damage due to the large obstacle areas they affect.

Entrainment of ambient air along the upper surface is a major retarding effect and has been studied in laboratory experiments, albeit mostly in water tanks, confining them to the Boussinesq regime of low relative density difference between the flow and the ambient fluid. However, little is known from direct measurements about the rate of snow suspension from a dense or fluidised flow or the snow cover, which is a crucial quantity in numerical modelling. Small-scale experiments by Bozhinskiy and Sukhanov (1998) with fine powders on a steep slope have perhaps come closest to simulate the evolution of a natural avalanche, but not all scaling issues could be resolved and there was no instrumentation to study the internal dynamics of the flows.

For these reasons, work in SATSIE has focused on a model system that does not reproduce all properties of real avalanches to scale but allows to study some of the fundamental properties of the transition. Flows of small expanded polystyrene particles or fine snow grains have been used on a relatively small chute that could be set up in a coldroom (in a collaboration with SLF, Switzerland). To compensate partly for the settling velocity that is far too high in comparison to real PSAs, much steeper slopes of 40–90° were used. In this way it was possible to achieve different degrees of suspension ranging from none, for slopes below a critical angle, to total, for vertical slopes. The three-dimensional structure of the flows has been analysed using video cameras and the software developed in Task 2.2. The air pressure in front of and inside the flows was also measured and was used to deduce the interior flow structure, see page 79. The data obtained in this way were important for testing the theoretical analysis of pressure signals and flow pattens presented in (McElwaine, 2005). That paper extends earlier work by von Kármán and Benjamin to gravity-driven flows on arbitrary slopes and shows how inviscid flow theory is able to determine many features of suspension flows. The main findings, confirmed by the laboratory experiments, are as follows:

- The front angle of avalanches should be 60° even on steep slopes with large internal velocities.

- The Froude number $\mathrm{Fr} = u/\sqrt{gh} \approx \sqrt{2}$, for a steady avalanche for any slope, where h is defined as the vertical distance between the top and bottom of the avalanche.
- Interaction with the ambient fluid cannot stop lateral spreading of an avalanche.
- The pressure evolution at a fixed location in or near the avalanche follows a typical pattern of a rise as the avalanche approaches, a drop to values well below ambient pressure as it passes over the observation point, and finally a return to ambient pressure in the wake. The avalanche velocity and size can be inferred from the shape of this dipole-like pattern.

McElwaine and Turnbull (2005b) show how the theory can be applied to full-scale PSAs using the pressure measurements made with the novel air-pressure sensors installed at Vallée de la Sionne. One may also try to test the prediction of a constant Froude number of $\sqrt{2}$ by analysing video footage from dry-snow avalanches with a strongly developed suspension layer. As shown by (Turnbull and McElwaine, 2006), the very long but extremely dilute turbulent wake and intrinsic difficulties of photogrammetry on somewhat ill-defined "soft" objects like a PSA do not allow one to obtain unambiguous results from the data, and there are further ambiguities in defining the Froude number in a meaningful way when large quantities of snow are being entrained along the path. It was nevertheless found that the front velocity stays nearly constant over large distances and that the avalanche volume seems to increase with the cube of the travel distance, as predicted by plume theory.

Many of the presently used numerical PSA models are sophisticated 3D codes that require long computation times even on today's computers, yet make it difficult to grasp some of the apparently quite simple properties of these flows. It was therefore interesting to study whether a simple model can capture these properties of real PSA events. Turnbull et al. (2006) chose the Kulikovskiy–Sveshnikova–Beghin model, a variant of which (Beghin and Olagne, 1991) has routinely been used by ETNA in consulting work (Rapin, 1995). It can be characterised as a block model where the block has a fixed shape but variable size and density. A consistent way of deriving it from the full Navier–Stokes-type of equations was demonstrated and analytic solutions were obtained for nearly realistic situations. Comparison with data from Vallée de la Sionne met with mixed success, but it remains to be seen to which degree this is due to uncertainties in the data on entrainment and other quantities.

Numerical models for hazard mapping

As mentioned in Sect. 6.3.1, it appeared premature to combine all innovations regarding flow-regime transitions, rheology and entrainment/deposition in a single model. ETNA's model MN2L incorporates the findings from Col du Lac Blanc, a physical entrainment model and coupling to a powder-snow avalanche module whereas NGI's D2FRAM features the possibility of flow-regime transitions and takes terrain curvature fully into account. Both models use the shallow-water (a. k. a. Saint-Venant) approach to obtain depth-integrated equations along a one-dimensional path of variable inclination (embedded in a two-dimensional space with one horizontal and one vertical dimension) or on a two-dimensional curved surface (embedded in three-dimensional space).

MN2L describes the evolution of three layers, namely (i) the snow cover at rest (index 0), which can be entrained or deposited, (ii) the dense core of the avalanche (index 1), and (iii) the suspension layer (the "powder-snow cloud", index 2). Mass exchange can take place between (i) and (ii), (ii) and (iii), and also between (i) and (iii) if the suspension layer is ahead of the dense core. Simplifying to one spatial dimension (x), the snow cover depth h_0 evolves as

$$\frac{dh_0}{dt} = -\phi_{e/d}\frac{\rho_1}{\rho_0} \tag{6.2}$$

where $\phi_{e/d}$ is the entrainment/deposition velocity. The balance equations of the dense layer read

$$\frac{\partial h_1}{\partial t} + \frac{\partial h_1 u_1}{\partial x} = \phi_{e/d} \tag{6.3}$$

for the mass conservation and

$$\frac{\partial h_1 u_1}{\partial t} + \frac{\partial k_1 h_1 u_1^2}{\partial x} = h_1 g \sin\theta - \frac{\partial K g h_1^2/2}{\partial x} - \mathrm{sgn}(u)\mu_{\mathrm{eff}} g h_1 \cos\theta \tag{6.4}$$

for the momentum conservation (leaving out centrifugal forces for simplicity). $\theta(x)$ is the slope angle, $k_1 = \mathcal{O}(1)$ (and k_2 used below) a so-called Boussinesq coefficient, which can be calculated from the velocity profile function. For μ_{eff}, the expression (6.1) is to be used, with coefficients possibly adapted to the situation. K is the earth-pressure coefficient and can a priori be specified in several ways, $K = 1$ corresponding to hydrostatic earth pressure.

In the suspension layer, the density is not constant because particle concentration changes. Therefore separate balance equations are solved for the volume (air plus snow) and the snow mass (in terms of the volumetric snow concentration c). A single momentum balance is used because the settling velocities of the snow grains are small:

$$\frac{\partial h_2}{\partial t} + \frac{\partial h_2 u_2}{\partial x} = e_w |u_2|, \tag{6.5}$$

$$\frac{\partial h_2 c}{\partial t} + \frac{\partial h_2 c u_2}{\partial x} = -w_s c^{(b)} + c_{*,\mathrm{salt}} C_D u_2, \tag{6.6}$$

$$\frac{\partial h_2 u_2}{\partial t} + \frac{\partial k_2 h_2 u_2^2}{\partial x} = R h_2 g \sin\theta - R\frac{\partial c g h_2^2/2}{\partial x} - \mathrm{sgn}(u) C_D^2 u_2^2. \tag{6.7}$$

$R = \rho_s/\rho_a - 1$ is the relative density difference between particles and air, C_D is the drag coefficient for the surface below the suspension layer, $c^{(b)}$ is the concentration at the bottom of the suspension layer, e_w is the air entrainment velocity at the upper surface of the suspension layer, and w_s denotes the settling velocity of snow grains at the bottom of the cloud.

The saltation layer is collapsed to an interface condition between the dense and suspension layers. Results from Aeolian saltation have been used to specify appropriate empirical expressions for $u_{*,\mathrm{salt}}$ and c_{salt}, the shear velocity and concentration in the saltation layer, respectively: $u_{*,\mathrm{salt}} = C_D \max(|u_1|, |u_2|)$, while $c_{\mathrm{salt}} = 0$ below a threshold velocity and $c_{\mathrm{salt}} = $ const. above a limit velocity.

A particularly interesting component of MN2L is its entrainment/deposition model (Naaim et al., 2004). Bed entrainment is conceptually divided into two phases (which occur simultaneously at the upper surface of the snowcover and in the strongly sheared bottom layer of the flow, respectively). In phase 1, if the shear stress exerted on the snowcover by the avalanche exceeds the shear strength, σ_{cr}, of the snowcover, erosion occurs in the sense that the bonds between snow grains are broken but the eroded snow is not yet set in motion and entrained by the avalanche flow. The threshold condition thus is

$$\mu_{\mathrm{eff}}(h, u)\rho g \cos\theta > \sigma_{\mathrm{cr}} + \mu_{\mathrm{eff}}(h, 0)\rho g \cos\theta, \tag{6.8}$$

provided the corresponding slice of the flow is accelerating, $\tan\theta - K\partial h/\partial x > \mu_{\mathrm{eff}}(h, 0)$. The expression $\rho g h \mu_{\mathrm{eff}}(h, u)$ represents the frictional shear stress exerted by the flow on the snow cover; on the other side of the equation, the cohesion of the material and the maximum static frictional shear stress combine. If erosion occurs, the cohesive shear strength of the eroded material immediately drops to zero.

Phase 2 describes the entrainment of the eroded material, i. e., its acceleration (and mixing with the flow). There are two key observations: (i) The rate of entrainment is determined, not by the erosion rate, but by the shear stress in the bottom layer that is available for accelerating the eroded material. (ii) The entrainment rate, the shear rate at the interface to the bed and the shear stress difference between the flow and the bed must be related consistently for momentum conservation to hold during entrainment. We do not give the somewhat lengthy expression for ϕ_e/d here but refer to (Naaim et al., 2004). Issler and Jóhannesson (2006) have since carried this analysis one step further to obtain the mean flow velocity, the velocity profile and the entrainment rate self-consistently from the rheology.

MN2L has been implemented in 1D and 2D versions, extensively validated and subsequently applied to many practical problems (Naaim et al., 2004). In a simplified version without the suspension layer, it

has been incorporated as a module into a spreadsheet application for hazard mapping which has been distributed to professionals of the French service RTM in charge of most hazard mapping in the French mountain territory. On request, qualified individuals can obtain a copy from ETNA.

D2FRAM is presently formulated as a one-layer model, but extension to a multi-layer model with entrainment/deposition similar to MN2L will be straightforward. The main conceptual difference from traditional depth-averaged models is the variable density $\bar{\rho}$, which requires an additional equation to be specified and solved[3]. In the 1D case (extension to 2D is straightforward) the mass balance and the momentum balance in the flow direction are written as

$$\frac{\partial \bar{\rho} h}{\partial t} + \frac{\partial \bar{\rho} h \bar{u}}{\partial x} = 0, \tag{6.9}$$

$$\frac{\partial \bar{\rho} h \bar{u}}{\partial t} + \frac{\partial k_1 \bar{\rho} h \bar{u}^2}{\partial x} = \bar{\rho} h g \sin\theta(x) - \sigma_{xz}^{(b)} + \frac{\partial h \bar{\sigma}_{xx}}{\partial x}. \tag{6.10}$$

x is the co-ordinate along the path, $\theta(x)$ the local slope angle, $\bar{u}$ the depth-averaged velocity and g the gravitational acceleration. The Boussinesq coefficient f_1 can be determined once approximate velocity and density profiles $u_1(x,z,t) = \bar{u}(x,t)\, f_u(z/h)$ and $\rho(x,z,t) = \bar{\rho}(x,t)\, f_\rho(z/h)$ have been prescribed. The depth-averaged longitudinal normal stress $\bar{\sigma}_{xx}$ and the bottom shear stress $\sigma_{xz}^{(b)}$ are obtained from the rheological equations, to be discussed shortly.

A shortcut for $\bar{\rho}$ is to assume that the avalanche, at each point and time, tries to adjust its density to the (local instantaneous) equilibrium density $\rho_{eq}(x,t)$ and behaves like an overdamped harmonic oscillator characterised by a relaxation time τ:

$$\frac{\partial \bar{\rho}}{\partial t} + \bar{u}\frac{\partial \bar{\rho}}{\partial x} = \frac{\bar{\rho}}{\tau}\left(1 - \frac{\bar{\rho}}{\rho_{eq}}\right). \tag{6.11}$$

The relaxation constant τ has to be adjusted empirically; it is expected to be of the order of 1 s.

A more complete dynamical solution of the density evolution maintains the assumption of uniform density across the depth of the flow but abandons the hydrostatic pressure assumption implicitly made if only eqs. (6.9) and (6.10) are used, but not the momentum balance in the z-direction. The latter, expressed in terms of the depth-averaged vertical velocity $\bar{w}$, reads

$$\frac{\partial \rho h \bar{w}}{\partial t} + \frac{\partial k_2 \rho h \bar{w} \bar{u}}{\partial x} = -\rho h g \cos\theta(x) - \sigma_{zz}^{(b)} + \frac{\partial h \bar{\sigma}_{xz}}{\partial x}. \tag{6.12}$$

If $\bar{\rho}$ were known, $\bar{w}$ could be calculated. The missing equation is now obtained by transforming the so-called kinematic boundary condition

$$\frac{\partial h}{\partial t} + u^{(s)}\frac{\partial h}{\partial x} = w^{(s)}, \tag{6.13}$$

which formulates the condition that the motion of the boundary $h(x,t)$ be determined by the motion of the uppermost flow particles. The boundary value (index (s)) of the velocity is determined by the profile functions as $u^{(s)} = \bar{u}\, f_u(1)$ and $w^{(s)} = \bar{w}\, f_w(1)$. After some algebra, (6.13) turns into

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \bar{u}}{\partial x} = \frac{\bar{\rho}}{h}\left((1 - f_u(1))\bar{u}\frac{\partial h}{\partial x} - f_w(1)\bar{w}\right). \tag{6.14}$$

This more complete solution allows to go beyond the hydrostatic approximation and to calculate normal loads on the ground more accurately, but it remains to be seen whether these advantages justify the additional complexity and computational effort.

[3]More precisely, the variables in D2FRAM are $\sqrt{g}\rho$, $\sqrt{g}\rho h$, $\sqrt{g}\rho h u^i$ where $g(x,y)$ is the determinant of the metric tensor $g_{ij}(x,y)$ and accounts for the spatial variation of the surface element $dA = \sqrt{g}\,dx\,dy$ in curvilinear co-ordinates. Ordinary partial derivatives are to be replaced by so-called covariant derivatives, etc. For the sake of simplicity, we shall suppress all complications arising from the full use of curvilinear co-ordinates. These are rather technical and are not relevant for the present discussion. A detailed treatment is given in (Issler, 2006).

The equations presented above are general in the sense that they can be used with any rheology, provided expressions are given for the stresses in terms of the density and other field variables, so that ρ_{eq} can be calculated, and compatible velocity and density profiles are prescribed. The specific rheology used in D2FRAM is derived from the NIS model (Norem et al., 1987; Irgens, 2000). It combines quasi-static granular yield behaviour (rate-independent Mohr–Coulomb dry friction) with collisional granular behaviour (Bagnoldian stresses proportional to the square of the shear rate) and plastic properties (yield strength independent of normal stress). Specialised to simple shear in the x-z-plane with shear rate $\dot\gamma = \partial u/\partial z$, it can be written as

$$\begin{aligned}
\sigma_{xx} &= -p_e - \rho(m_3 + m_2 - m_1)\dot\gamma^2, &(6.15)\\
\sigma_{yy} &= -p_e - \rho m_3 \dot\gamma^2, &(6.16)\\
\sigma_{zz} &= -p_e - \rho(m_3 + m_2)\dot\gamma^2, &(6.17)\\
\sigma_{xz} &= -\mathrm{sgn}(\dot\gamma)[a + bp_e + \rho m \dot\gamma^2]. &(6.18)
\end{aligned}$$

Furthermore, in this case $\sigma_{xy} = \sigma_{yz} = 0$. p_e is the so-called effective pressure transmitted by enduring grain–grain contacts and is obtained only when the boundary conditions are applied. a and b are the cohesion and the Coulomb friction coefficient, respectively. The four rheological parameters m, m_1, m_2, m_3 have to fulfil certain inequalities for consistency (Issler et al., 2006) and must be specified as functions of the density (they will also strongly depend on the temperature, of course).

Specifying the density dependence of these parameters is not an easy task, as may be gathered from the discussion given on pages 80 ff. No direct measurements of all stress components exist generally for granular materials because the density is difficult to control. Snow presents even more practical difficulties (see page 18) and its properties vary drastically with temperature and density. For this reason, results from a theoretical study (Pasquarell et al., 1988) and a discrete-element simulation (Campbell and Gong, 1986) have been used as a starting point. For the reasons discussed by Rajchenbach (2004), both approaches may be flawed at densities close to the dense packing limit, but binary collisions should be a good approximation at lower densities relevant in the transition to the fluidised state. Furthermore, both studies are for two-dimensional granular systems. Nevertheless, the qualitative density dependence of the parameters should be correct:

- The stresses grow as the square of the shear rate.
- At high densities, the collisional contribution dominates over the translational one, at low densities the converse holds.
- The coefficients m and $m_{1,2,3}$ diverge in both the dense and the dilute limit (the stress nevertheless going to zero in the latter case).
- The density dependence of m_1 and m_2 is the same in these models, but m grows more slowly with increasing density than m_1 and m_2.

This has the consequence that the effective friction coefficient $\mu_{\mathrm{eff}} = \sigma_{xz}/\sigma_{zz}$ decreases slowly as the density increases. The practical consequence is the following: Given enough time, the avalanche adjusts its velocity so that $\mu_{\mathrm{eff}} = \tan\theta$. After an abrupt slope-angle increase, the velocity and the shear rate increase and the density has to decrease until the new equilibrium is reached. At low and very high densities, the density change is relatively small for a given slope-angle change, but in the intermediate range much larger density changes occur. This corresponds to the transition to or from the fluidised state.

The numerical implementation of D2FRAM has not been completed yet. A second-order non-oscillating central-differences scheme will be used, which was originally developed for the Eglit and Savage–Hutter models (Tai et al., 2001, 2002; Gray et al., 2003). Application of this scheme to D2FRAM poses additional challenges because instabilities may arise at the edge of the flow where $h \to 0$ could lead to unphysically high shear rates and enormous stresses. This problem is currently being studied with a simplified code.

Some practical consequences predicted by D2FRAM may be anticipated already now:

- As avalanches exhibit higher velocities in the head than in the body (even in traditional models), the head is much more likely to fluidise than the body, in accordance with all observations.
- Fluidisation leads to larger flow depths, hence higher mean velocities are attained than predicted for the non-fluidised regime at the same shear rate.
- The fluidised head of an avalanche is therefore much more likely to overflow a dam than the bulk of the mass inthe dense body.
- The mode predicts different pressure distribution in the runout zone, the fluidised part has long runout, but moderate pressure due to its low density; the dense core may stop much earlier than predicted by conventional models.

Experiments and theory of avalanche–dam impact and practical recommendations

This activity was originally planned to be fairly limited and very practically oriented towards a handbook on dam design that would summarise all results obtained in the predecessor project CADZIE and compare them to new measurements at Ryggfonn. However, it turned out that many important questions could not be fully answered within CADZIE and that chute experiments begun at the University of Bristol in collaboration with IMOR yielded most intriguing results on the importance of shocks of the hydraulic-jump type both in catching and deflecting dams. For these two reasons, the study of avalanche–obstacle interactions became one of the major activities of SATSIE. Writing a handbook on dam design proved more difficult and time-consuming than originally assumed and could not be finished within the project period, but a draft in an advanced stage is available and will be finalised in the second half of 2006.

Traditional design criteria—e. g., see (Salm et al., 1990)—treat the run-up on a dam from the point of view of mass-point mechanics: The dam should have a minimum height of $H = h_{sc} + h_a + v_a^2 \sin^2 \phi/(2g\lambda)$, where h_{sc} is the expected height of the snow cover at the dam (possibly including deposits from preceding avalanches), h_a and v_a are the avalanche flow depth and velocity just before the dam, g the gravitational acceleration, ϕ the deflection angle (90° for catching dams), and the factor λ accounts for energy losses in the impact. No objective method based on point-mass dynamics is available to determine the empirical parameter λ. A fundamental problem with the point-mass view is that it neglects interaction of different parts of the avalanche where they clearly are important, particularly where snow masses deflected down the side of a deflecting dam collide with oncoming snow masses or where snow from the rear hits snow from the front already stopped by a catching dam.

In hydraulic terms, snow avalanches are supercritical flows except just before stopping. Obstacles may turn them into subcritical flows, and this transition is effected through a *hydraulic jump*—a shock where the velocity and flow height change discontinuously in mathematical idealisation and the necessary amount of energy is dissipated by means of turbulence and/or compaction. The key consideration is that mass and momentum conservation across the shock determine the downstream flow height and velocity and, implicitly, the energy lost during the impact. Shock theory does take into account the interaction of different pars of the avalanche and succeeds in determining the equivalent of λ, if it is indeed applicable to avalanche–dam interactions.

An extensive series of laboratory experiments with granular flows impacting on obstacles (see the PhD thesis (Hákonardóttir, 2004) for summary of previous work, extensive discussion of new experiments and their analysis) have ascertained that this is indeed the case for dry granular flows at high Froude numbers. In fact, the effective inelasticity in collisions of grain assemblies allows the needed energy dissipation to occur in much smaller volumes than in water so that the granular shocks are much closer to their mathematical idealisations. Experiments at SLF's and ETNA's snow chutes have been carried out since. Interpretation of the results from ETNA's experiments requires more analysis due to the narrow channel used in those experiments, but in general shock theory appears to be applicable to snow avalanches as well. However, splashing and increased suspension of particles in air may also occur then (Hákonardóttir et al., 2003). Note that shock theory also predicts that there are limits beyond which no shock can form,

e. g. if the approach velocity is too high or the deflection angle of the deflecting dam is too large. In these cases, supercritical overflow occurs.

Based on the assumption that shock theory is applicable within its proper limits, design criteria have been proposed in the draft handbook. The most important ones are as follows:

1. Estimate appropriate design values for the velocity and flow depth of the avalanche at the location of the dam, u_1 , h_1, and for the snow depth on the terrain upstream of the dam, h_s. For a deflection dam, determine the deflecting angle ϕ. For a catching dam, $\phi = 90^\circ$.
2. Compute the Froude number of the flow, $\mathrm{Fr} = u_1/\sqrt{gh_1 \cos\psi}$, and the component of the velocity normal to the dam axis, $u_\perp = u_1 \sin\phi$, where ψ is the terrain slope upstream of the dam. Determine the momentum loss coefficient k according to

$$k = 0.75 \ \text{ for } \ \alpha > 60^\circ, \qquad k = 0.75 + 0.1 \cdot (60^\circ \text{âĹŠ} \alpha)/30^\circ \ \text{ for } \ 30^\circ \geq \alpha \geq 60^\circ. \tag{6.19}$$

   The coefficient k represents the loss of momentum normal to the dam axis in the impact and depends on the angle of the upper dam side with respect to the terrain α.
3. Compute the sum of the critical dam height, H_{cr}, and the corresponding critical flow depth, h_{cr}, according to

$$h_r = H_{cr} + h_{cr} = \frac{h_1}{k} + \frac{(u_1 \sin\phi)^2}{2g\cos\psi} k^2 \left(1 - k^{-2} (\mathrm{Fr} \sin\phi)^{\text{âĹŠ}4/3}\right). \tag{6.20}$$

   The dam height above the snow cover must be greater than the run-up height $h_r = H_{cr} + h_{cr}$. If the dam height above the snow cover is lower than H_{cr}, the avalanche may overflow the dam in a super-critical state. If the dam height is lower than $H_{cr} + h_{cr}$, the front of the avalanche may overflow the dam while a shock is being formed. Note that some overflow may occur in the initial impact due to splashing even when this criterion is satisfied.
4. Compute the flow depth, h_2, downstream of a shock above the dam according to

$$\frac{h_2}{h_1} = \frac{1}{3} \left(2\sqrt{6\mathrm{Fr}_\perp^2 + 4} \, \cos\delta + 1\right). \tag{6.21}$$

   where δ is given by

$$\delta = \frac{1}{3} \left[\frac{\pi}{2} - \arctan \left(\frac{9\,\mathrm{Fr}_\perp^2 - 8}{\mathrm{Fr}_\perp \sqrt{27(16 + 13\,\mathrm{Fr}_\perp^2 + 8\,\mathrm{Fr}_\perp^4}} \right) \right]. \tag{6.22}$$

   The dam height above the snow cover, h_r , must also be greater than h_2.
5. For a deflecting dam, check whether an attached, stationary, oblique shock is dynamically possible by verifying that the deflecting angle, ϕ, is smaller than the maximum deflecting angle, $\phi_{\max}$, corresponding to the Froude number Fr. It is recommended that ϕ be at least 10° smaller than $\phi_{\max}$.
6. For a catching dam, compute the available storage space normal to the dam axis up-stream of the dam per unit length along the dam, assuming a deposit surface inclination in the range 0–10°. For dams where dry-snow avalanches are expected, deposit slopes close to 0° should be used, but for locations where wetter avalanches are typical slopes up to 10° can be chosen. The storage per unit width or storage area must be larger than the volume of the avalanche divided by its width.
7. For a deflecting dam, evaluate the extent of the region affected by increased run-out distance caused by the interaction of the avalanche with the dam. The construction of the dam leads to increased avalanche risk within this area.

These criteria are compatible with the granular chute flow experiments.

Another source of information for validating the theoretical run-up ranges is data about overflow of avalanches over the 16 m high catching dam at the full-scale experimental site at Ryggfonn in western Norway (Gauer and Kristensen, 2005a). Their re-analysis of data collected over 20 years produced a tantalisingly simple scaling law for the over-run length $l_{\rm or}$ vs. the approach kinetic energy per unit mass, $u_b^2/2$:

$$\frac{l_{\rm or}}{h_{\rm fb}} \approx b_1 \frac{u_b^2}{2gh_{\rm fb}} - b_0, \tag{6.23}$$

where $h_{\rm fb}$ is the freeboard height of the dam just before the event. For the selected Ryggfonn avalanches, a good fit of the data was obtained for $b_1 = 2.56$ and $b_0 = 1.41$. We may rewrite this equation as an energy balance between the initial kinetic energy, the energy loss during impact and the frictional energy loss from the dam to stand-still:

$$\frac{u_b^2}{2} = \frac{b_0}{b_1} g h_{\rm fb} + \frac{1}{b_1} g l_{\rm or}. \tag{6.24}$$

$1/b_1 \approx 0.4$ is then interpreted as the effective friction coefficient after the avalanche has passed the dam, and $b_0/b_1 \approx 0.55$ is the fraction of the potential energy corresponding to the dam height that was lost in the impact. According to Gauer and Kristensen (2005a), there are indications that chute experiments might show similar scaling, but confirming this conjecture needs careful analysis of the conditions of each single experiment.

The values obtained at Ryggfonn correspond to rather long over-run distances compared to the inferred velocity at the impact with the dam and are difficult to reconcile with the theoretical run-up ranges described by the design criteria above. It is also difficult to reconcile with various other observations of run-up of natural avalanches on dams and other obstacles. The effectiveness of catching dams to completely stop snow avalanches seems to be particularly uncertain. These inconsistencies may to some extent be explained by the uncertainty of the data and of back-calculated velocities and flow depths, but this is unlikely to be the only explanation. Further full-scale experiments and further theoretical analysis are required to improve this unsatisfactory situation.

6.3.3 Summary of deliverables

We list here all the scientific deliverables of SATSIE, with only a brief description for reports as they are listed along with the scientific articles in Sect. 6.6, where the abstract is also reproduced.

Deliverable D1: *Web-site and meta-data archive.*

The project website has been hosted by the University of Leeds at the URL *http://www.leeds.ac.uk/satsie* from the start of the project. It has since been continually updated and enhanced and will remain functional into the foreseeable future. In the publicly accessible sections, it gives an overview of the project, presents the team members, lists the publications from SATSIE (which are downloadable as PDF files if copyright permits) and gives brief introductions to selected topics of avalanche dynamics for the interested lay public. The private section has served as a repository for minutes of meeting, draft papers, etc. The site has seen over 4,000 visits since it became online and has served as a major means of communication within the SATSIE consortium. It is expected that it will maintain much of this functionality also in the future.

After some researching and an extended discussion within the consortium that included setting up an agreement on the use of experimental data from the project, a general data format for storing experimental data was agreed upon and a data archive was created at Cambridge University that is not simply a meta-data archive but contains veritable data to which all consortium members have free access. In this way, it serves as a backup archive to the data collections at the various institutes as well. At the conclusion of the project, it contained more than 100 GB of data transformed

into Common Data Format (CDF), which is an established, open and architecture-independent standard. CDF is at the same time a very flexible format so that not only experimental data from sensors but images, videos or simulation results can be included; the file header conveys all the necessary information for accessing the data correctly. For virtually all existing or extinct computer systems, open-source libraries and programs for reading and manipulating CDF archives are available so that these data will remain accessible indefinitely.

Deliverable D6: *Summary publication on sensor design and data analysis techniques.*
It collects project memos and peer-reviewed publications on new data analysis methods and on the design of certain sensor types, in particular the multi-directional air pressure sensors developed by J. N. McElwaine in collaboration with SLF, Davos.

Deliverable D8: *Updated report on European avalanche test sites.*
Edited by M. Barbolini and D. Issler. contributions by T. Jóhannesson and K. M. Hákonardóttir (IMOR), K. Lied, D. Issler and P. Gauer (NGI), M. Naaim and T. Faug (Cemagref–ETNA), L. Natale, ;. Barbolini, F. Cappabianca and M. Pagliardi (UP-DIIA), L. Rammer (AIATR), B. Sovilla and K. Platzer (WSL–SLF), E. Suriñach, G. Furdada, F. Sabot and I. Vilajosana (UB–DGG).

This report updates and extends the report "European Avalanche Test Sites. Overview and Analysis in View of Coordinated Experiments" from the 4th Framework Programme project SAME, finished in 1998. The sections on the large-scale sites Vallée de la Sionne and Ryggfonn and the large snow chute at Weissfluhjoch, Davos have been substantially revised to include the latest installations. There are new sections on the instrumented dams in Flateyri (Iceland) and Taconnaz (France) as well as on the granular chutes in Bristol, Reykjavík, Pavia, Davos and Alpe d'Huez / Col du Lac Blanc. The report gives the necessary background information for assessing the significance of measurements from these facilities.

Deliverable D10: *Documentation of instrumentation scheme and installation work at the selected sites.*
Edited by M. Barbolini (UP–DIIA). Contributions by T. Jóhannesson (IMOR), K. Lied and P. Gauer (NGI), M. Naaim and T. Faug (Cemagref–ETNA), L. Natale, M. Barbolini, F. Cappabianca and M. Pagliardi (UP–DIIA), E. Suriñach and I. Vilajosana (UB–DGG).

This report describes the instrumentation work carried out during the SATSIE Project (Avalanche Studies and Model Validation in Europe, Contract no. CT2002–00059) in a group of selected experimental facilities, ranging from full-scale avalanche sites (Ryggfonn in Norway, Taconnaz in France and Flateyri in Iceland) to small-scale facilities, including the snow chute located in high-mountain terrain (Col du Lac Blanc, France) and laboratory granular chutes (Pavia, Italy).

A substantial technical and financial effort was made in order to improve the instrumentation of the mentioned facilities and to be able to perform comprehensive experimental investigations on the dynamics of avalanches, with special attention paid to poorly known aspects such as flow regimes, erosion processes and interaction of the flow with obstacles of various sizes and shapes. The facilities have been selected so as to maximise the variety of the experiments that can be performed, especially varying the size from laboratory-scale to full-scale, whilst insuring that the experiments are repeatable and as easy as possible to perform. The instrumentation of the considered facilities has been consistently improved in order to obtain more complete and accurate information on the important physical processes of avalanche dynamics. The first experimental campaigns carried out during the project encouraged us to go on with our work, with the belief that improving the knowledge of the phenomenon is an essential step towards improved simulation models, which are crucial tools for reducing avalanche risk and increasing the safety and quality of life of people living in avalanche-prone terrain in Europe and elsewhere.

Deliverable D11: *Summary publication on results from small and large-scale experiments.*
Edited by C. J. Keylock (SGUL), with contributions by M. Barbolini (UP–DIIA), M. E. Eglit (MSU), T. Faug, M. Naaim (Cemagref–ETNA), P. Gauer, C. B. Harbitz, D. Issler, K. Lied, (NGI),

K. M. Hákonardóttir, T. Jóhannesson (IMOR), M. Kern, B. Sovilla (WSL–SLF), J. N. McElwaine (CU–DAMTP), and K. Nishimura (Nagaoka).

In the early stage of SATSIE, a review article on inferences on the dynamics of dry-snow avalanches from experiments was published (Issler, 2003). The SATSIE group considered it timely to attempt to write another review paper that would include the new results from the project itself as well as the viewpoints of a larger group of authors,and to publish it in a high-profile earth-sciences journal. Two draft versions have been written and circulated among the group. Work is continuing beyond the project duration, and we expect to submit the paper towards the end of 2006.

Deliverable D12: *Summary publication on avalanche / dam interaction measurements.*
Edited by C. J. Keylock (SGUL). Contributions by P. Gauer, D. Issler, K. Lied, K. Kristensen, H. Iwe, E. Lied (NGI), T. Jóhannesson (IMOR), L. Rammer (AIATR), and H. Schreiber (TUG–INW).

While measurements of avalanche–dam impacts at full scale have been made at Ryggfonn, the data are incomplete and therefore often hard to interpret because of the lack of comprehensive instrumentation. Chute experiments do not have these limitations, but it is far from obvious how to scale the results to real avalanches. This report summarises the salient features of measurement results at small and large scales and discusses the conditions under which the chute results might be transferable to the scale of natural avalanches. In particular, it discusses the parametrisation of overrun lengths suggested for Ryggfonn by Gauer et al. (2006) and relates it to the chute experiments. The report may serve as background information for readers of the Handbook on Dam Design (D14, see below) and may also become the starting point for a scientific paper.

Deliverable D13: *Models of specific processes in avalanche flow and sample modules for inclusion in numerical codes.*
ETNA's new dynamical model MN2L has been implemented in various versions: as 1D and 2D depth-averaged codes, with and without the powder-snow layer above the dense-flow layer. The experimental findings that inspired the model, its physical content and mathematical formulation,the mainfeatures of its numerical implementation and validation results have been presented at several conferences and in the papers (Naaim et al., 2003, 2004). The main features of the model are (i) an empirical rheology inferred from chute experiments with granular materials and snow, including a bi-linear velocity profile with a strongly sheared bottom layer and a much less sheared top layer, (ii) an entrainment/deposition module that is tightly integrated with the rheology and takes into account the forces needed to accelerate eroded bed material, and (iii) coupling between the dense-flow and suspension layers through a saltation layer formulated as an interface condition between the top ad bottom layers.

The 1D version of MN2L has been distributed to professionals of the French agency RTM who are involved in avalanche hazard mapping and who participated in an introductory course on the use of this model. The model is also made available to other interested parties upon request to Cemagref–ETNA. Brief user manuals have been written in French and English (see Deliverable D15).

The development of NGI's new Dynamical Two-Flow-Regime Avalanche Model (D2FRAM) has been taking longer than anticipated due to the inherent difficulties of formulating the density dependence of the rheological parameters and the density evolution equation and due to limited manpower. At the end of the project, two reports were in an advanced stage of preparation: One details the rheological concept and the basic depth-averaged equations in the limiting case of flow on a uniformly inclined surface (Issler et al., 2006). The other (Issler, 2006) discusses the changes in the equations due to the use of curvilinear co-ordinates on general curved surfaces and various ways of implementing these changes efficiently in the numerical model. These reports will be sent to the Scientific Officer when completed in late summer or early autumn of 2006. Furthermore, a prototype FORTRAN code has been developed for the well-known NIS model (Norem et al., 1987,

1989) in one dimension to test a modern higher-order shock-capturing numerical scheme that has so far been implemented only for the simpler Savage–Hutter and Eglit models and is described in (Gray et al., 1999; Tai et al., 2002). It presently serves to test the stability of the scheme under the NIS rheology; it will be extended to two dimensions and adapted to the more complicated D2FRAM in the near future.

The full equation set of D2FRAM, the principles of the numerical implementation and the main results of the validation will be published in peer-reviewed scientific journals. The code will be made available to the members of the SATSIE consortium. NGI has not decided yet concerning distribution to a wider audience because the complex questions of liability, service obligations, quality assurance, suitability for not adequately trained persons and competitiveness can be resolved more easily when the product is finished.

Deliverable D14: *Handbook on deflection and catching dam design.*
A draft version of the deliverable, entitled *The design of avalanche protection dams. Recent practical and theoretical developments* has been produced and is included with this report. For a more detailed description, see Sect. 6.6, page 102. The consortium decided to distribute the handbook only when a few issues connected to recent chute experiments have been understood more thoroughly. The Scientific Officer will be kept informed on the progress in finalising the handbook.

Deliverable D15: *User manuals for advanced models in avalanche hazard mapping.*
A concise user manual has been written for MN2L from ETNA in French and translated into English. The English version is contained on the Compact Disc attached to this report. The user manual for D2FRAM can be written only after the model has been fully implemented and validated. A copy will be sent to the Scientific Officer upon completion.

Deliverable D18: *European Summer University 2004 on avalanche hazard mapping.*
The European Summer University 2004 on snow avalanches was held in Courmayeur, Val d'Aoste, Italy, from 18 to 24 September 2004, with approximately 35 advanced students and avalanche professionals from France, Italy and Spain participating. The Pôle Grenoblois d'Etude et de Recherche pour la Prévention des Risques Naturels (PGRN, *http://www.risknat.org*) provided all the logistic and administrative support while SATSIE team member M. Barbolini (UP–DIIA) was responsible for the scientific content of the course and was also one of the lecturers, together with several other team members. The lectures were put into practice by extensive field work, during which the participants were tutored by the lecturers from SATSIE and other specialists. Extensive lecture notes were produced and distributed to the participants on paper as well as electronically. This course material may be reused in future base courses on snow avalanches.

During the 2004 base course, only a small fraction of the new results from SATSIE could be presented to the participants by M. Naaim, due to limited lecture time and the research that was still ongoing. This circumstance and the general success of the 2004 course convinced the SATSIE consortium to plan an advanced course, more specifically focused on the new research results and numerical modelling. As it will take place only after the conclusion of SATSIE, other sources for financing the costs for the lecturers and part of the facilities had to be searched for. This time-consuming process led to postponement of the course from September 2006 to September 2007. PGRN will again be responsible for the administrative and logistic support. A preliminary course outline was decided upon during the last project meeting in Seyðisfjörður, Iceland in September 2005. A planning committee has been set up to refine the course content, appoint the lecturers and establish the timetable.

6.4 Conclusions

As the project SATSIE has come to its conclusion, one may assert that the original objectives have been achieved, with a few deliverables requiring a little more time to fully mature before they are released to end-users. In order to lay a firm foundation for avalanche hazard mitigation measures, a number of basic scientific questions of avalanche dynamics have been studied in a highly co-ordinated way. The results from SATSIE account for a substantial part of the world-wide work on avalanche dynamics during the years 2002–2006. The close collaboration within the project opened the door to instrument developments, experiments and products for end-users that would nave been impossible otherwise. The consortium has worked together exceptionally well, and it is suggested to explore ways for transforming it into a European research network.

Below, specific aspects of our assessment of the project outcome are developed in more depth.

6.4.1 Comparison of objectives and achievements

SATSIE proceeded closely along the planned lines and achieved its objectives to a very high degree. The points in which complete success could not (yet) be achieved are the following:

- *Development of high-performance FMCW radar for avalanche measurements:* The device was developed and performed up to expectations in laboratory tests, but proved to be vulnerable to the harsh winter environment. This is a case of the “devil hiding in the details” and can undoubtedly be corrected soon.
- *Development of air-pressure sensors for PSA measurements:* Very similar problems were encountered with these sensors, and they will be corrected likewise as soon as funds become available.
- *Development of snow rheometer:* It was clear from the beginning that fundamental difficulties might be encountered, but the potential gain from such an instrument warranted the risk. So far, the problem of shear band formation could not be controlled sufficiently. Further modifications of the apparatus have been proposed and will be tested.
- *Development of new models for hazard mapping:* MN2L, ETNA’s new dynamical avalanche model, has been completed and validated. In this repsect, the objective has been met. NGI’s new model D2FRAM is in an advanced development stage and will hopefully reach the testing phase in the fall of 2006. Illness and manpower shortage were mainly responsible for the incurred delay, but the prospects for attaining the goal are very good.
- *Review publication on knowledge on snow avalanches from experiments:* A draft report has been written, thus the specified deliverable has been produced. It is felt, however, that this work has the potential of becoming a major contribution to avalanche science and deserves more discussion and revision before publication.
- *Handbook on Dam Design:* Much more work has been done in SATSIE on this topic than was anticipated at the beginning. The main reasons are that results from the predecessor project CADZIE were less conclusive than expected and that experiments on impacts in granular flows opened the door to a new approach to the problem through shock theory. A number of issues arising from the comparison of the small-scale experiments and the theory they have inspired to the full-scale measurements from Ryggfonn should, however, be settled before the handbook with its potentially far-reaching consequences is distributed to a wider audience. Thus, in some sense, the delay in this deliverable is due to unexpected progress.

In summary, the original objectives proved realistic and were essentially achieved. In a few cases, additional work is required after the project termination to bring the work to conclusion and resolve remaining technical problems or achieve a higher degree of certainty in the results.

6.4.2 Scientific importance of the achieved results and their implications for future research

The hallmark of SATSIE was the physical approach to the key problems of avalanche dynamics, the quest for understanding the fundamental mechanisms rather than applying purely empirical knowledge. This approach has a long-standing tradition in avalanche science, but it is perhaps for the first time that an avalanche project of this size, channelling a significant portion of European avalanche research, has been so clearly focused on understanding the physical processes. To this end, experiments were conducted at different scales, analysed and compared in novel ways and combined with a substantial amount of theoretical work. This comprehensive method was a major reason for the success of SATSIE and should be pursued in the future.

We feel that the degree of physical insight into the phenomenon that is being gained in avalanche dynamics—with a major contribution from SATSIE—may inspire and motivate similar projects focusing on other types of geophysical mass flows, particularly debris flows, pyroclastic flows and rock avalanches. The environmental conditions in those types of flows are even more difficult than in snow avalanches, but it appears that at least some of the experimental techniques might be adaptable.

On the modelling side, MN2L and D2FRAM represent a significant step forward in that they attempt to incorporate the emerging experimental knowledge on the structure and rheology of avalanches. MN2L as a two-layer model with entainment/deposition and D2FRAM with its capability of modelling flow-regime transitions are more complex than almost all models that have been used hitherto. Once D2FRAM has been validated, its potential impact on hazard maps that are elaborated according to the widely differing national regulations needs to be assessed. Both models should be developed further when new experimental date become available. Depending on the accumulating experience with MN2L and D2FRAM, a new model that combines the best features of these two codes might be formulated and implemented in the future.

6.4.3 Socio-economic relevance, strategic aspects and policy implications

As mentioned before, this project could not be expected to produce immediately measurable financial returns. Its social importance is in its contribution to sustainable development of Europe’s mountain areas where a sufficient degree of safety from natural hazards is a prerequisite for continued human presence. Hence SATSIE will be considered a success if it contributes to a situation where there is *no* visible change in that the mountain population does not emigrate to urban areas because they consider their living conditions too unsafe.

SATSIE was the fourth in a series of European Union RTD projects in various Framework Programmes in which largely the same partner institutions from most snow and avalanche research institutions in Europe have collaborated for almost fifteen years. The benefits of this continuity have been very apparent in SATSIE: Mutual trust and friendship between the team members not only made the project meetings very enjoyable experiences, but the team work and communication in general were very efficient and data sharing, which had been a major discussion point in previous projects, presented no problems in SATSIE. A significant number of papers with authors from several institutions are testimony to this.

The importance of this “human capital” asset should not be undervalued. In a time of shrinking budgets, collaboration across the borders is the key to maintain a sufficient research activity and to disseminate new knowledge also among partners who were not actively involved in that particular research. Most of

the consortium members are too small to maintain expertise in all the subfields that might be required at some point in the future for specific projects and tasks in their own country—having close personal ties to foreign experts on these particular questions may often solve the problem in a short time. The maintenance of advanced research infrastructure is only possible in a collaborative effort, as became clear already during the preparation of the proposal for SATSIE.

In consideration of this, it would seem highly desirable to maintain the close contacts created in these four EU projects, even if future Framework Programmes set different priorities that require different consortia. Formation of a Research Network appears as a promising step. However, even in times of easy electronic communication, personal meetings cannot be completely replaced, and such a Research Network would need sufficient funding for regular workshops modelled after the very successful Work Package meeting in Leeds and Tyriheim in 2003. An additional objective for such a network could be to organise regular courses for avalanche professionals. The base course on snow avalanches in 2004 and the advanced course on modelling and hazard mapping in 2007 could become a platform for continued teaching activities and outreach.

Snow avalanches have many features in common with other hazardous gravity mass flows, notably debris flows, rock avalanches and pyroclastic flows. Experiments on snow avalanches are not easy, but they are less difficult than experiments on those other hazards. This circumstance suggests that a well established Research Network on snow avalanches could also serve as a crystallisation point for more co-ordinated European research activities in the field of gravity mass flows in general.

Finally, it should be mentioned that discussions about homogenising the multitude of national regulations and practices in avalanche hazard mapping and mitigation have borne very little fruit up to now. It is too early to tell how much impact the Handbook on Dam Design, which is currently under preparation, and the new dynamical models will have in this respect, but there is a real chance that such tools, which were elaborated in close collaboration, will actually be used in the countries represented in the consortium and will over time lead to a convergence of practices, which in turn may prepare the ground for common European guidelines.

6.5 Dissemination and exploitation of the results

Particular thought had to be given to the best way of disseminating the insights and results from SATSIE. One may distinguish three categories of results that can and should be publicised in specific ways for optimum valorisation of this project:

1. *Scientific results:* The traditional venues for publicising scientific results are contributions to conferences (oral presentations or posters) and publications in scientific journals. On both counts, SATSIE has been very active and visible. SATSIE team members were major contributors to the Symposium on Snow and Avalanches of the International Glaciological Society (IGS) in Davos, Switzerland in the spring of 2003 and to the sessions on avalanches at the General Assemblies of the European Geophysical Union in Nice (2003, 2004) and Vienna (2005, 2006). As the list of publications (pages 13 ff.) shows, a large number of peer-reviewed publications in reputed journals have already appeared, and a substantial number will still follow.

   Only modest efforts have been made to publicise the project and its results in the mass media. A camera team from a Norwegian television channel filmed during some of the campaigns at Ryggfonn. With a more aggressive strategy, more mass-media coverage could have been obtained, but there were also strong reasons not to seek this attention: First, the main results were to be expected in the last phase of the project and in many cases their outcome was not clear until very late. Second, the preparation of a feature film that is understandable for a wide target audience, yet essentially correct and meaningful in its scientific content, is a highly labour-intensive task for the host institution and other consortium members—even if an experienced and well-informed journalist is directing the film.

2. *Tools for hazard mapping and protection structures:* The results falling into this category are presently (i) the dynamical models MN2L-1D and MN2L-2D, (ii) the handbook on dam design, and (iii) the European Summer University courses on snow avalanche hazard mapping.

   Some of the consortium partners (NGI, IMOR, AIATR, ETNA and DIIA) either are the institutions officially in charge of avalanche hazard mapping in their respective countries or are heavily involved in consulting for the authorities. These partners thus are end-users or have very close ties to them. In Great Britain, avalanche problems are of very limited importance, whereas Spain does not have legislation mandating avalanche hazard mapping and therefore there are not yet any well-defined end-users. In these circumstances, informing all consortium partners of new results, e. g. during the project meetings, is in itself already an effective means of dissemination. In order to reach free professionals—an important group in Switzerland and to a lesser degree in Austria, France, Italy and Iceland—open-enrolment courses and practical publications such as a handbook were deemed the most effective ways of dissemination. In countries where the local consortium partner does not have well established ties to these groups, professional organisations might be used as distribution channels. In addition, background material such as many project reports can be downloaded from the project web site.

3. *Instrumentation for monitoring and alarm systems:* At the end of the project, the range-gating Doppler radar, which represents an evolutionary step from earlier designs produced by INW, is functional and has proven its capabilities as an excellent research tool. Without further changes, it can be used for monitoring avalanche paths that threaten traffic routes and triggering an alarm in the case of an event. However, the instrument is more expensive than simpler continuous-wave Doppler radar systems such as the one purchased by IMOR from AlpuG GmbH in Switzerland for monitoring the Flateyri avalanche path. Presumably, future orders for INW's radar will mostly come from Austria's Organisation for Torrent and Avalanche Control, to which ties have been established long ago.

   The commercial potential of the FMCW radar is expected to be larger than for the Doppler radar,

but this is contingent on the development of a rugged and low-price version. NGI plans to collaborate with a SME for the manufacture, marketing and servicing of those radars. In Norway, the main potential customer are the State Road Authorities, to which close ties exist. In other countries, contacts may be established through partners from the SATSIE consortium, through participation in topical fairs, advertisements in publications of professional organisations, etc. From these venues, the marketing strategy will have to be developed in close collaboration with the SME that will produce the devices.

An obvious and important line along which to exploit the results from SATSIE is the future research of the consortium members themselves. The main research themes of SATSIE could not be exhausted during the project and remain central problems that should be pursued in the quest for better avalanche protection methods. Clearly, additional topics such as determination of typical initial conditions (i. e., release area and release depth as a function of return period) should be given higher priority than hitherto so they can catch up with avalanche dynamics, but the latter should not be neglected. At the Seyðisfjörður meeting, all consortium partners expressed their desire and willingness to participate in a future coordinated project that picks up where SATSIE had to stop.

6.6 Main literature

This section a selection of publications that came out of SATSIE, gives the bibliographic reference and reproduces the abstracts where available. Reports that are not published in a journal as well as a few papers upon which the publishers have not imposed stringent copyright restrictions are available as PDF files from the SATSIE website `http://www.leeds.ac.uk/satsie`. Many of the other papers can be accessed quickly by clicking on the doi link in the website. Furthermore, all papers and reports are collected on the compact disc delivered with this report. A more complete list of publications from the SATSIE project is contained in Section 2, pages 13 ff. of this report.

1. *Sensor Design and Data Analysis Techniques for Snow Avalanches*
   Edited by J. N. McElwaine.

   This report is Deliverable D6 from SATSIE. It collects project memos and peer-reviewed publications on new data analysis methods and on the design of certain sensor types, in particular the multi-directional air pressure sensors developed by J. N. McElwaine in collaboration with SLF, Davos.

   Chapter 2 discusses how avalanches can best be filmed. The main issues are the type of camera, camera positioning and what are the optimal camera settings. Chapter 3 describes an algorithm for calculating the motion of avalanches from films based on changepoint determination. The software for this is available as part of the SATSIE project. The method is particularly suitable for tracking granular flows and other scientific experiments. Chapters 5 and 6 discuss internal measurements of flow velocity using opto-electronic sensors that consist of infrared LEDs and photo-transistors. There has been little discussion of the optimal design of such instruments and the best analysis techniques. This chapter discusses some of the different sources of error that arise and how these can be mitigated. Chapter 6 discusses how these sensors can be applied to measure two-dimensional velocities. The effects of acceleration and structure in the underlying field of reflectance are carefully accounted for. An algorithm is proposed for calculating the continuous velocity vector of an avalanche and a sketch of the mathematical analysis is given. The chapter concludes by suggesting design criteria for such sensors. Chapter 7 discusses the design and analysis of air pressure sensors. Our design consists of a differential pressure transducer, with a high frequency response, built into a specially designed housing unit. We mounted this 10 m from the ground on a measurement mast in the Vallée de la Sionne avalanche test site in Switzerland. We present an analysis of the sensor response and an interpretation of the signals in terms of simple flow fields. We show how these data can be used to deduce information about the speed, size and location of the avalanches using a dipole approximation.

2. *Avalanche Test Sites and Research Equipment in Europe. An Updated Overview.*
   Edited by M. Barbolini and D.Issler. Contributions by T. Jóhannesson and K. M. Hákonardóttir (IMOR), K. Lied, D. Issler and P. Gauer (NGI), M. Naaim and T. Faug (Cemagref-ETNA), L. Natale, M. Barbolini, F. Cappabianca and M. Pagliardi (UP-DIIA), L. Rammer (AIATR), B. Sovilla and K. Platzer (SLF), E. Suriñach, G. Furdada, F. Sabot and I. Vilajosana (UB-DGG).

   This report updates and extends an earlier overview report "European Avalanche Test Sites. Overview and Analysis in View of Coordinated Experiments", edited by D. Issler in 1998 in the course of the 4th Framework Programme project SAME. That report was published both on a Compact Disc issued by the EU Commission and as Mitteilung SLF No. 59 (1999) by the Swiss Federal Institute for Snow and Avalanche Research, Davos, Switzerland. The new report is Deliverable D8 from the project SATSIE.

   It describes in some detail all the major facilities available in Europe for avalanche research, including some test sites such as the Lukmanier Pass site in Switzerland or Monte Pizzac in Arabba, Italy, that produced important results in the past but are no longer in use. Much of the information

given in the report is important for assessing the circumstances under which certain results have been obtained but is not easily obtainable from the published literature. The report also includes tables comparing the properties of various test sites and an analysis of their potential for future discoveries.

3. *Results from Small and Large Scale Experiments on Snow Avalanche Dynamics*
   Edited by C. J. Keylock (SGUL), with contributions by M. Barbolini (UP-DIIA), M. E. Eglit (MSU), T. Faug, M. Naaim (Cemagref-ETNA), P. Gauer, C. B. Harbitz, D. Issler, K. Lied, (NGI), K. M. Hákonardóttir, T. Jóhannesson (IMOR), M. Kern, B. Sovilla (WSL-SLF), J. N. McElwaine (CU-DAMTP), and K. Nishimura (Nagaoka).

   This is Deliverable D11 from SATSIE.

   In this article we focus on the dynamics of the flowing, dry snow avalanche. In particular, we examine the available field evidence and consider the insights that may be gained from laboratory experimentation, making links to recent work on the physics of granular materials. There is a long history of scientific measurements of snow avalanche dynamics, although it is only more recently that the emphasis of this research has shifted away from obtaining data for improving the design of engineering structures towards gaining a greater understanding of avalanche dynamics. This change has parallelled the reduction in equipment cost and data processing time, which has meant that it has become possible to deploy sensor technologies at densities approaching those needed to gain insights into flow dynamics.

   While the powder component of an avalanche is clearly visible, the existence of a dense layer beneath is also well-known, and this bipartite structure forms the basis for various dynamics models, experimental data have shown that a typical dry avalanche has a tripartite structure with a saltation layer developing between the dense and powder layers. The suspension layer or powder cloud typically has a density of $3\,\mathrm{kg\,m^{-3}}$, with densities of $30\,\mathrm{kg\,m^{-3}}$ and $300\,\mathrm{kg\,m^{-3}}$ for the saltation and flowing layers, respectively. These values may be compared to densities of $30\,\mathrm{kg\,m^{-3}}$ for freshly fallen snow, $200\,\mathrm{kg\,m^{-3}}$ for a typical snow slab and $917\,\mathrm{kg\,m^{-3}}$ for ice. This tripartite division can be complicated further by considering the flowing, dense layer to be further split into a rapidly sheared basal region underlying a plug layer where the shear rate is dramatically reduced. However, it has yet to be firmly established if such a layer exists or the extent to which shearing is dominated by slip at the bed. A detailed description of the conditions in the basal layer is very much a priority research question at present.

   The remainder of this report begins by discussing the frictional and collisional properties of snow, before examining field data on the dense, saltation and powder snow layers of the avalanche. Understanding avalanche mass balance is of great practical importance and is considered next, before some results concerning the interaction between avalanches and obstacles are presented.

4. *Summary publication on avalanche / dam interaction measurements*
   Edited by C. J. Keylock (SGUL). Contributions by P. Gauer, D. Issler, K. Lied, K. Kristensen, H. Iwe, E. Lied (NGI), T. Jóhannesson (IMOR), L. Rammer (AIATR), and H. Schreiber (INW).

   This is Deliverable D12 from SATSIE.

   This short report aims to provide a comparison between the large-scale measurements undertaken at the Ryggfonn test site as part of the SATSIE project with experiments on impacts with obstacles performed in experimental chutes. Hence, it draws together experimental data collected as part of Workpackages 4.1 and 4.2 of the SATSIE project. It commences with a brief report of the characteristics of avalanches observed at Ryggfonn as reported by Gauer et al. (submitted). It then proceeds to consider avalanche-dam interactions more explicitly in terms of a framework described by Lied et al. (2002) and Gauer et al. (unpublished). A comparison of the results from Ryggfonn and experiments undertaken at Bristol University is then provided and this is supplemented with an examination of some results from the test chutes in Pavia, Italy. A description of the Ryggfonn site

and the Pavia chutes is given in Barbolini and Issler (2005) and Lied et al. (2002), although a brief review is provided here. A comprehensive investigation into avalanche dam design is presented in Deliverable 14 (The design of avalanche protection dams: Practical and theoretical developments and results). Hence, our aims here are rather more modest—we describe some simple analyses that can be undertaken on the existing avalanche data, compare the results to granular flow experiments and then discuss the relevance of such experiments for snow avalanche dam analysis.

5. *The design of avalanche protection dams. Recent practical and theoretical developments*. Draft version.
   Edited by T. Jóhannesson (IMOR). Contributions by U. Domaas, P. Gauer, C. B. Harbitz, K. Lied (NGI), K. M. Hákonardóttir, T. Jóhannesson (IMOR), C. J. Keylock (SGUL), L. Rammer (AIATR), A. Bouchet, T. Faug, F. Naaim-Bouvet, M. Naaim (Cemagref-ETNA), M. Barbolini, and M. Pagliardi (UP-DIIA).

   This is Deliverable D14 from SATSIE, treating the design of dams and other protection measures in the run-out zones of wet- and dry-snow avalanches. It summarises recent theoretical developments and results of field and laboratory studies and combines them with traditional design guidelines and principles to formulate design recommendations.

   The report first discusses the communication between avalanche experts, on the one hand, and local authorities and the public, on the other, during the design of avalanche protection measures. The next two sections are an overview of traditional design principles for avalanche dams and a summary of avalanche dynamics with an emphasis on the interaction of avalanches with obstacles. The design of deflecting dams, catching dams and breaking mounds is treated in the next four sections. They are followed by a section about dams as protection measures against powder snow avalanches and sections about impact loads on walls and on masts and mast-like obstacles, and about static snow loads. Next, numerical modelling of snow avalanches is treated with special regard to modelling of flow over or around dams and obstacles; geotechnical aspects of dam design are also discussed. Several appendices give examples of the design of deflecting and catching dams, demonstrate combined protection measures, present geotechnical examples, describe the overrun of avalanches over the catching dam at Ryggfonn in Norway, summarise the Swiss and Norwegian recommendations about loads on structures, and compare the laws and regulations about avalanche protection measures and hazard zoning in connection with such measures in several European countries.

6. *Experimental information on the dynamics of dry-snow avalanches*
   D. Issler. 2003.
   In K. Hutter and N. Kirchner (eds.), *Dynamic Response of Granular and Porous Materials under Large and Catastrophic Deformations*, Lecture Notes in Applied and Computational Mechanics, vol. 11. Springer, Berlin, Germany. Pages 109–160.

   This paper is a first step towards a synoptic analysis of the experimental information on snow avalanche flow provided by field observations and dedicated experiments over the past 60 years. Both full-size tests in instrumented avalanche tracks and laboratory experiments with snow or substitute materials are used to extract information on two major questions: (i) Which flow regimes are possible in avalanches and under which conditions do they occur? (ii) By which mechanisms and at which rate do avalanches entrain snow from the snow cover? The major types of sensors used in avalanche experiments are briefly discussed, and it is seen that a large variety of sensors and experimental techniques—including laboratory experiments—have to be combined in order to obtain definitive answers to the open questions.

7. *Experimental study of erosion processes in snow avalanches*
   M. Barbolini, A. Biancardi, F. Cappabianca, L. Natale and M. Pagliardi. 2005.
   Cold Regions Science and Technology **43** (1–2), 1–9; doi:10.1016/j.coldregions.2005.01.007.

In order to better understand the mechanics of erosive processes characteristic of snow avalanche flows, a series of laboratory experiments were carried out. In these experiments a mass of dry granular material was released in a channel with rectangular cross-section. A part of the channel was covered with an erodible layer. The experiments were recorded with a high-speed digital camera and the interaction between the flowing material and the erodible bed was studied using different colours for the two materials. The records allowed an extremely detailed high-frequency visualisation of the phenomenon. Observations of the erosion mechanisms as well as measurements of the erosion rates were performed. The results of the experiments were analysed and interpreted with respect to some theoretical erosion models from the literature.

8. *A low cost system for the estimation of concentration and velocity profiles in rapid dry granular flows*
M. Barbolini, A. Biancardi, L. Natale and M. Pagliardi. 2005.
Cold Regions Science and Technology **43** (1–2), 49–61; doi:10.1016/j.coldregions.2005.05.003.

A series of laboratory experiments with granular material has been carried out at the Hydraulic and Environmental Engineering Department of the University of Pavia (Italy). The aim was to investigate the internal properties of fast moving dry granular flows, with particular attention paid to the measurements of concentration and velocity profiles. A low-cost acquisition system was built using a Pulnix digital camera and off-the-shelf components and integrating only open-source software around a GNU/Linux operating system. Different techniques for the measurements of velocity and concentration profiles have been proposed and tested. The flow regimes have been investigated and a distinction between "front", "body" and "tail" of the moving mass has been established in terms of the flow concentration. Additionally, a comparison with experimental results and theories found in the literature has been outlined.

9. *Experimental and numerical study of granular flow and fence interaction*
T. Faug, M. Naaim and F. Naaim-Bouvet (Cemagref-ETNA). 2004.
Annals of Glaciology **38**, 135–138.

Dense snow avalanches are regarded as dry granular flows. This paper presents experimental and numerical modelling of deposition processes occurring when a gravity-driven granular flow meets a fence. A specific experimental device was set up, and a numerical model based on shallow-water theory and including a deposition model was used. Both tools were used to quantify how the retained volume upstream of the fence is influenced by the channel inclination and the obstacle height. We identified two regimes depending on the slope angle. In the slope-angle range where a steady flow is possible, the retained volume has two contributions: deposition along the channel due to the roughness of the bed and deposition due to the fence. The retained volume results only from the fence effects for higher slopes. The effects of the slope on the retained volume also showed these two regimes. For low slopes, the retained volume decreases strongly with increasing slope. Comparisons between the experiments and computed data showed good agreement concerning the effect of fence height on the retained volume.

10. *An equation for spreading length, center of mass and maximum run-out shortenings of dense avalanche flows by vertical obstacles*
T. Faug, M. Naaim and F. Naaim-Bouvet (Cemagref-ETNA). 2004.
Cold Regions Science and Technology **39**, 141–151; doi:10.1016/j.coldregions.2004.04.002.

In this paper, we consider dense snow avalanches interacting with a defense structure. The maximum run-out distance of dense snow avalanches is the sum of the center of mass run-out and the spreading length. We make the simplifying assumptions that the center of mass run-out is mainly dependent on the velocity of the avalanche flow and the spreading length is mainly linked to the volume of the deposit. The obstacle reduces momentum of the avalanche by (i) velocity reduction and (ii) mass reduction by deposition upstream of the obstacle. The first effect leads to the shortening of the center of mass run-out and the second one explains the spreading length

decrease. Therefore, the maximum run-out reduction is a function of both velocity and volume reductions. An equation is proposed to predict the maximum run-out reduction. This equation is tested on small-scale granular avalanches. For laboratory experiments with confined granular avalanches interacting with a thin vertical dam, velocity and volume reductions are expressed as simple functions of the vertical dam height. The equation for the maximum run-out shortening is then calibrated on experimental data and used to predict the velocity reduction and the critical height for which the granular avalanche is entirely stopped by the vertical dam.

11. *Oblique shocks in rapid granular flows*
K. M. Hákonardóttir, and A. J. Hogg. 2005.
Physics of Fluids **17**, 077101; doi:10.1063/1.1950688.

The interaction between rapid, free-surface granular flows and deflecting dams is investigated by laboratory experimentation and by the formulation and analysis of a shallow-layer model of the motion. It is found that uniform, downslope flows of grains are deflected to flow parallel to the barrier and that upstream of the barrier, the flow state undergoes an abrupt transition whereby its depth, velocity, and direction of motion change. These oblique shocks are investigated for a range of Froude numbers and for a range of angles between the deflector and the direction of steepest descent. The experimental results are found to be in good agreement with predictions from the shallow-layer theory. Experiments were also conducted with rapid, free-surface flows of water. They reveal not only similarities between the steady deflection patterns of the water and grain flows, but also some differences in the nature of their initial interaction. A simple interpretation for this is given in terms of the relatively high pressures that develop during the initial impact of the incompressible water with the impermeable barrier. Deflecting dams are deployed to defend against large-scale snow avalanches and these results are applied to this situation.

12. *Dense snow avalanche modeling: flow, erosion, deposition and obstacle effects*
M. Naaim, F. Naaim-Bouvet, T. Faug and A. Bouchet (Cemagref-ETNA). 2004.
Cold Regions Science and Technology **39** (2–3), 193–204; doi:10.1016/j.coldregions.2004.07.001.

Dense avalanches made of dry snow were studied as granular flows, through the development and use of a numerical model based on the shallow water theory. Friction was represented by a phenomenological law resulting from the recent progress in the field of snow avalanche constitutive laws. Using this friction formulation and assumptions similar to those employed in the shallow water theory, a simple model describing erosion and deposition was formulated and tested. The system of equations obtained was solved using a numerical scheme of finite volumes. The model was then tested on experimental data obtained in the laboratory. Relative good agreement was observed between the simulated and experimental data. An avalanche path where 153 avalanches were observed over the last century was chosen. The dry friction values have been determined providing the coincidence of the calculated and observed distances. We analysed the statistical distribution of the obtained dry friction coefficient and compared the obtained range to the range obtained by Casassa et al. (1991). Afterwards, we studied the effect of a dam of different heights placed at two locations in the path and analysed its effectiveness in terms of volume reduction and run-out distance, demonstrating that the friction coefficient has a prevailing role on both the dynamics of the avalanche and the effectiveness of the dam.

13. *Possible erosion mechanisms in snow avalanches*
P. Gauer and D. Issler (NGI). 2004.
Annals of Glaciology **38**, 384–392.

Snow erosion and entrainment processes in avalanches are classified according to their mechanisms, the flow regimes in which they occur, and their spatial position within the avalanche. Simple, but process-specific models are proposed for erosion by impacts, abrasion, plowing, and blasting. On the basis of order-of-magnitude estimates, the first three mechanisms are clearly expected to be important. The fourth mechanism stipulates that the compaction of the snowcover

ahead of the avalanche leads to the flow of escaping air just in front of the avalanche that may disrupt the snowcover and support formation of a saltation layer. The effects of this hypothetical mechanism resemble those of the plowing mechanism. All mechanisms depend strongly on the snow properties, but with plausible parameter values, erosion rates at or above the experimentally found rates are obtained. The entrainment rate of an avalanche is most often limited by the shear stress needed to accelerate the eroded snow to avalanche speed.

14. *On full-scale avalanche measurements at the Ryggfonn test site, Norway*
P. Gauer, D. Issler, K. Lied, K. Kristensen, H. Iwe, E. Lied (NGI), L. Rammer (AIATR), and H. Schreiber (INW). 2006.
Accepted for publication in *Cold Regions Science and Technology*.

Avalanche measurements carried out at the Ryggfonn test site, Norway, during several winter seasons are analyzed with emphasis on recognizing different flow regimes and estimating flow densities. Measurements include impact pressure readings from load cells mounted at two locations within the track and stress readings from load plates flush with the upstream slope of a catching dam. Pressure measurements were combined with velocity estimates based on cross correlations between the load cell readings and, in several cases, on Doppler radar measurements. In most cases a saltation (fluidized) layer in front of a more dense part could be identified. Doppler radar measurements confirm a fast moving head, in some instants preceded by a slower snout, and decreasing speed from the head to the tail. Calculated accelerations (decelerations) indicate that the effective friction parameter varies strongly and depends on the flow regime.

15. *Constrained surrogate time series with preservation of the mean and variance structure*
C. J. Keylock (SGUL). 2006.
Physical Review E **73**, 036707; doi:10.1103/PhysRevE.73.036707.

A method is presented for generating surrogates that are constrained realizations of a time series but which preserve the local mean and variance of the original signal. The method is based on the popular iterated amplitude adjusted Fourier transform method but makes use of a wavelet transform to constrain behavior in the time domain. Using this new method it is possible to test for local changes in the nonlinear properties of the signal. We present an example for a change in Hurst exponent in a time series produced by fractional Brownian motion.

16. *Rotational flow in gravity current heads*
J. N. McElwaine. 2005.
Philosophical Transactions of the Royal Society of London, Series A **363**, 1603–1623; doi:10.1098/rsta.2005.1597.

The structure of gravity currents and plumes, in an unbounded ambient, on a slope of arbitrary angle is analysed. Inviscid, rotational flow solutions in a wedge are used to study the flow near the front of a current, and used to show that the Froude number is $\sqrt{2}$ and the angle of the front to the slope is 60°. This extends the result of von Kármán (1940) to arbitrary slope angles and large internal current velocities. The predictions of the theory are briefly compared with experiments and used to explain the large negative (relative to ambient) pressures involved in avalanches.

17. *Snow avalanche speed determination using seismic methods*
I. Vilajosana, G. Khazaradze, E. Suriñach, E. Lied and K. Kristensen
Submitted to *Cold Regions Science and Technology*

The method of avalanche speed determination presented in this paper is based on cross-correlation and time-frequency analysis techniques. The data used in this study come from the Ryggfonn (Norway) avalanche experimental site operated by the Norwegian Geotechnical Institute (NGI), and recorded by an array of 6 geophones buried along the main avalanche path during the 2003–2004 and 2004–2005 winter seasons. Specifically, we examine the speeds of 11 different events, characterized by size and snow type. The results obtained are compared with independent speed

estimates from CW-radar and pressure plate measurements. As a result of these comparisons our method was validated and has proved to be successful and robust in all cases. We detected a systematic behaviour in the speed evolution among different types of avalanches. Specifically, we found that whereas dry/mixed type flow events display a complex type of speed evolution in the study area with a gradual acceleration and an abrupt deceleration, the speed of the wet snow avalanches decreases with distance in an approximately linear fashion. This generalization holds for different size events. Dry/mixed type avalanches traversed the last 320 m upstream of the dam in 8 to 18 s and reached speeds up to 50 m/s, whereas wet avalanches needed from 50 to 80 s, with maximum speeds around 10 m/s.

Appendix A

Content of the attached Compact Disc

A.1 Final Report

Final_report/final_report.pdf SATSIE Final Report (this document in PDF format)

Final_report/Text/final_report.tex SATSIE Final Report, LaTeX master source file.

Final_report/Text/fr_*.tex SATSIE Final Report, LaTeX text files called by final_report.tex.

Final_report/Text/ar4_*.tex SATSIE Final Report, LaTeX text files concerning the fourth annual report, called by final_report.tex.

Final_report/Text/*.bib SATSIE Final Report, BibTeX source files with bibliographical databases.

Final_report/Text/report_EU.cls Modified LaTeX style file for reports.

Final_report/Text/tweaklist.sty Small macro package used by final_report.tex.

Final_report/Images/*.eps Graphics files for Final Report, in Encapsulated PostScript format.

Final_report/Images/*.jpg Graphics files for Final Report, in Joint Photographic Experts Group (JPEG) format.

Final_report/Images/*.pdf Graphics files for Final Report, in Portable Document Format (PDF).

Final_report/Images/*.png Graphics files for Final Report, in Portable Network Graphics (PNG) format.

A.2 SATSIE Reports

Reports/satsie_d06.pdf Deliverable D6: Sensor Design and Data Analysis Techniques for Snow Avalanches. Edited by J. N. McElwaine.

Reports/satsie_d08.pdf Deliverable D8: Avalanche Test Sites and Research Equipment in Europe. An Updated Overview. Edited by M. Barbolini and D.Issler. Contributions by T. Jóhannesson and K. M. Hákonardóttir (IMOR), K. Lied, D. Issler and P. Gauer (NGI), M. Naaim and T. Faug (Cemagref-ETNA), L. Natale, M. Barbolini, F. Cappabianca and M. Pagliardi (UP-DIIA), L. Rammer (AIATR), B. Sovilla and K. Platzer (SLF), E. Suriñach, G. Furdada, F. Sabot and I. Vilajosana (UB-DGG).

Reports/satsie_d10.pdf Deliverable D10: Documentation of instrumentation and installation details. Edited by M. Barbolini (UP-DIIA). Contributions by T. Jóhannesson (IMOR), K. Lied and P. Gauer (NGI), M. Naaim and T. Faug (Cemagref-ETNA), L. Natale, M. Barbolini, F. Cappabianca and M. Pagliardi (UP-DIIA), and E. Suriñach and I. Vilajosana (UB-DGG).

Reports/satsie_d11.pdf Deliverable D11: Results from Small and Large Scale Experiments on Snow Avalanche Dynamics. Edited by C. J. Keylock (SGUL. Contributions by M. Barbolini (UP-DIIA), M. E. Eglit (MSU), T. Faug, M. Naaim (Cemagref-ETNA), P. Gauer, C. B. Harbitz, D. Issler, K. Lied, (NGI), K. M. Hákonardóttir, T. Jóhannesson (IMOR), M. Kern, B. Sovilla (WSL-SLF), J. N. McElwaine (CU-DAMTP), and K. Nishimura (Nagaoka).

Reports/satsie_d12.pdf Deliverable D12: Summary publication on avalanche / dam interaction measurements. Edited by C. J. Keylock (SGUL). Contributions by P. Gauer, D. Issler, K. Lied, K. Kristensen, H. Iwe, E. Lied (NGI), T. Jóhannesson (IMOR), L. Rammer (AIATR), and H. Schreiber (INW).

Reports/satsie_d14_draft.pdf Deliverable D14: The design of avalanche protection dams. Recent practical and theoretical developments. Draft version. Edited by T. Jóhannesson (IMOR). Contributions by U. Domaas, P. Gauer, C. B. Harbitz, K. Lied (NGI), K. M. Hákonardóttir, T. Jóhannesson (IMOR), C. J. Keylock (SGUL), L. Rammer (AIATR), A. Bouchet, T. Faug, F. Naaim-Bouvet, M. Naaim (Cemagref-ETNA), M. Barbolini, and M. Pagliardi (UP-DIIA).

Reports/satsie_d15.pdf Deliverable D15: Short user manual for the Cemagref dense snow avalanche model based on shallow water equations. Cemagref – Research Unit ETNA.

A.3 Published articles

Published/Barbolini_et_al_Entrainment.CRST.pdf Barbolini, M., A. Biancardi, F. Cappabianca, L. Natale and M. Pagliardi. 2005. Experimental study of erosion processes in snow avalanches. *Cold Regions Science and Technology* **43** (1–2), 1–9; *doi:10.1016/j.coldregions.2005.01.007*. (Has appeared in print since 2nd Annual Report.)

Published/Barbolini_et_al_Tracking.CRST.pdf Barbolini, M., A. Biancardi, L. Natale and M. Pagliardi. 2005. A low cost system for the estimation of concentration and velocity profiles in rapid dry granular flows. *Cold Regions Science and Technology* **43** (1–2), 49–61; *doi:10.1016/j.coldregions-.2005.05.003*. (Has appeared in print since 2nd Annual Report.)

Published/Cappabianca.PhD_Thesis.pdf La valutazione del rischio valanghivo attraverso la modellazione dinamica. PhD thesis of Federica Cappabianca, submitted to Engineering Faculty of the University of Pavia, Pavia, Italy. April 2006.

Published/Ghilardi_et_al_Impacts.RIVERFLOW.pdf Experiments on the impact process of dry and saturated mixtures against obstacles of various shapes. P. Ghilardi, M. Pagliardi and B. Zanuttigh. Accepted for publication in: *RIVERFLOW 2006, International Conference on Fluvial Hydraulics*, September 6–8, 2006, Lisboa, Portugal.

Published/Keylock_Surrogates.Phys_Rev_E.pdf Constrained surrogate time series with preservation of the mean and variance structure. C. J. Keylock. *Physical Review E* **73**, 036707.

Published/Turnbull_et_al_KSB.JGR_E.pdf The Kulikovskiy–Sveshnikova–Beghin model of powder snow avalanches: development and application. B. Turnbull, J. N. McElwaine and C. Ancey. Accepted for publication in *Journal of Geophysical Research – Earth Surface*.

A.4 Submitted or unpublished articles and other documents

Other/Issler_Report_curvature_draft.NGI.pdf Curvature effects in depth-averaged flow models on arbitrary topography. D. Issler. NGI Report 20021048–14, draft version.

Other/Issler_et_al_Report_regimes_draft.NGI.pdf Flow-regime transitions in granular gravity mass flows – an extension of the Norem–Irgens–Schieldrop Model. D. Issler, P. Gauer, A. S. Moe and F. Irgens. NGI Report 20021048–13, draft version.

Other/Issler_Johannesson_Entrainment_draft.NGI.pdf On the formulation of entrainment in gravity mass flow models. D. Issler and T. Jóhannesson. NGI Report 20021048–12, draft version, to be submitted for publication.

Other/Keylock_Wavelets.Physica_D.pdf Pseudo-periodic surrogate data generation using wavelet-based methods. C. J. Keylock. Submitted to *Physica D*.

Other/Turnbull_McElwaine_VdlS.J_Glaciol.pdf A comparison of powder snow avalanches at Vallée de la Sionne with plume theories. B. Turnbull1 and J. N. McElwaine. Submitted to *Journal of Glaciology*.

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Gauer, P. and D. Issler. 2004. Possible erosion mechanisms in snow avalanches. *Annals Glaciol.*, **38**, 384–392.

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Gauer, P. and K. Kristensen. 2005b. Avalanche Studies and Model Validation in Europe, SATSIE: Ryggfonn measurements Winter 2004/2005. NGI Report 20021048–8. N–0806 Oslo, Norway, Norwegian Geotechnical Institute.

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