

INTERREG IIIA: LMR-EPFL Project Report

Manzella Irene (1), Labiouse Vincent (1)

(1) Rock Mechanics Laboratory LMR, Swiss Federal Institute of Technology, 1015 Lausanne, Switzerland.

irene.manzella@epfl.ch, vincent.labiouse@epfl.ch

Table of contents

1. Introduction	2
2. Action C.1 - References	2
3. Action C.2 - Physical modelling: tests description and results	5
3.1. Experimental set-up and tests description	5
3.2. Measuring devices	6
Fringes projection method	7
3.3. Tests programme	9
3.4. Results interpretation	10
Granular materials and influence on deposit morphology	10
Volume and drop height	13
Releasing geometry	14
Consecutive releases	16
Resume table	19
3.5. Conclusions and future developments	20
4. Action C.2 - Physical modelling: simulation of a test with the different codes	21
4.1. Comparison between the codes results	21
Annex 1: Data sheet	24

1. Introduction

In the action C framework (study and modelling of rockslide runout with comparison of different codes) the EPFL rock mechanics laboratory is carrying out a research by means of a small scale physical model to study the main parameters influencing runout to verify or establish laws enable to describe these relationships and to better understand the complex rockslide phenomena.

As soon as rock avalanches are luckily not so frequent, in the research field there is a lack of well known real cases on which we could base proper back analysis studies or codes validations. For this reason, physical modelling can constitute a significant sample to fill up partly the lack of reliable data. Indeed, even if the quantitative interpretation of the results is not straightforward, owing to the difficulty in matching the scaling laws, laboratory experiments are very helpful for the phenomenology study and the assessment of relevant physical parameters as well as for numerical models validation and calibration.

They have the following advantages:

- test conditions and parameters are easy to control (good reproducibility)
- testing campaign can be organised in series to systematically isolate and investigate parameters influence

In this context the research carried out by the EPFL assumes an important role in the INTERREG project as soon as project partners and future users could employ the results obtained to validate their codes and to understand how and which parameters should be eventually introduced to ameliorate runout prediction and which factors could have a major influence on the results made by numerical modelling.

The Laboratory has been involved mainly in the following part of the project:

- action C.1: bibliographical study on rockslides runout physical modelling
- action C.2: model development and laboratory experiments

In the following chapters the specific activities carried out by the LMR-EPFL will be described in details.

2. Action C.1 - References

A document (see table 2-1) was compiled with a classification of some of the most significant references on granular and blocks flow physical modelling.

The classification is structured in order to give the expert reader the possibility to find out quickly the kind of experimental study which interests him following the path of the tests details given. For example if the reader is searching some references about 2D sand unsteady flow, he can find them out looking in the granular material section, 2D, unsteady flow and finally sorting the ones where sand has been used. In this case the results would be Davies and McSaveney (1999), Davies et al (1999) and Valentino et al (2004). The search can be even more specific if the reader is interested only in some particular test, with a certain amount of material, a specific range of slope inclination or drop height.

Naturally other kinds of classification are possible and the references included do not cover the entire field, but it has been tried to follow the needs encountered as experimental researchers.

The complete references list follows.

				Material, Diameter [mm]	Amount	Height [cm]	Slope	Reference
Granular material	2D	Steady flow	Small scale	Glass beads D=0.3	<7.2Kg/s/m	<130	<40°	Ancey et al (1997)
				Steel beads D=3	1200-1700 particles/s	~60<h<~80	18°-24°	Azanza et al (1997)
				Quartz sand D=0.035		50<h<90	33°	Bagnold (1954)
				Plastic spheres D=6	2230,1280 particles/s	~250 cm	42.75°	Drake (1990 and 1991)
				Sand, rock flour, polystyrene beads	200 Kg/s	400<h<700	28.4°,33.6°	Hungr, Morgesten (1984)
				Glass beads D=0.5,1.3,1.15		<100	20°-28°	Pouliquen (1999)
		Unsteady flow	Small scale	Glass, Vestolen, Quartz, marmor beads 2.5<D<5	1.5, 3 l	~ 200	Curved	Greve, Hutter (1993)
				Chick peas D=10	15000, 16000 peas	~90<h<~165	20°-50°	Bouzid (1999 and 2001)
				Debris?	V,1/19V			Broilli (1976)
				Gravel density=2650 kg/m ³	~9,~18dm ³	~200<h<350	27°-44°	Chu et al (1995)
				Silica sand D ₅₀ =0.19, gravel D ₅₀ =2	0.1-1-10-1000 l	~100<h<150	35°, 45°	Davies, McSaveney (1999) Davies et al (1999)
				Fine silica D=0.19	1.8 l	H _{CM} =14,21,35	45°	Davies, McSaveney (2002 and 2003)
				Glass, Vestolen, Quartz, marmor beads 2.5<D<5	1.5,2.5,3 l	~200	curved	Hutter, Koch (1991)
				Plastic particles D=4, glass beads D=3	500 to 5000gr		40°-60°	Hutter, Savage (1988)
				Glass, alumina, zirconia beads D=14	100 to 600 part.	~50<h<100	15°,25°	Okura et al (2000 and 2001)
				Ticino sand D=0.6	22.5 dm ³	~170	25°	Valentino et al (2004)
	3D	Unsteady flow	Small scale	Chick peas D=10	15000, 16000 peas	~90<h<~165	20°-50°	Bouzid (1999)
				Glass, Vestolen, Quartz, marmor beads 2.5<D<5	<3dm ³	~200	20°-60°	Greve et al (1994)
				Silt, dry ice (also oil, bentonite, thixotropic flow)	<160 cm ³	~60	41°	Hsü (1975)
				Dry quartz sand D=0.5	290 cm ³	~19.5	31.4°	Denlinger, Iverson (2001)
				Glass beads D=0.5	62,231,524 g	<100	19°-24°	Pouliquen, Fortierre (2002)
				Vestolen beads D=2-3.5, marble chips D=2-4, quartz chips D=4-5	<3 dm ³	~180	40°	Wieland et al (1999)
			Large scale	Water saturated sand and gravel	10 m ³	~5000	31°	Denlinger, Iverson (2001)
Blocks	3D	Unsteady flow	Small scale	Jointed mass, block of 36x36x110	~2dm ³		20°,28°,36°	Reik, Hesselmann (1976)
				Jointed mass, block of 120x120x30, 120x30x30	~2dm ³		35°, 40°	Rengers, Müller (1970)
			Large scale	Square block	0.001 to 1 m ³	290	35° and 20°	Okura et al (2000 and 2002)

table 2-1 : references scheme

AUTHORS	TITLE	YEAR	REFERENCES
Ancey C., Evesque P., Coussot P.	Analogy between granular flows down an inclined channel and the motion of a bead down a bumpy line	1997	<i>Powder & Grains</i> , p.475-478, 1997
Azanza E., Chevoir F., Moucheron P.	Experimental study of rapid granular flows in a two-dimensional channel	1997	<i>Powder & Grains</i> , p.475-478, 1997
Bagnold RA	Experiments on a gravity free dispersion of large solid spheres in Newtonian fluid under shear	1954	<i>PRSL V.225</i> , p.49-63, 1954
Bouزيد I	Contribution à l'étude des écoulements granulaires appliqués aux éboulements rocheux en grande masse	1999	<i>Thèse de Doctorat de l'Université Claude Bernard, Lyon</i> , 1999
Bouزيد I	A "monofluid" homogenization approach for highly dilatant granular flows. Application to massive rockfalls	2001	<i>Bulletin Labor. Ponts et chaussées</i> , V.232, ref.4351, p.31-44, May-June 2001
Broilli L.	Relations between scree slope morphometry and dynamics of accumulation processes	1976	<i>Rockfall dynamics and protective works effectiveness. Istituto Sperimentale Modelli E Strutture ISMES</i> , n°90, p. 11-23, 1976
Camponuovo	ISMES' experience on the model of S.Martino	1976	<i>Rockfall dynamics and protective works effectiveness. Istituto Sperimentale Modelli E Strutture ISMES</i> , n°90, p.25-38, 1976
Chu, T., Hill, G., McClung, D.M., Ngun, R., Sherkat, R.	Experiments on granular flows to predict avalanche run-up	1995	<i>CGJ V.32</i> , p.285-295, 1995
Davies T.R.H., McSaveney M.J.	Runout of dry granular avalanches	1999	<i>CGI,V.36</i> , p.313-320, 1999
Davies TRH, McSaveney MJ, Hodgson KA	A fragmentation-spreading model for long-runout rock avalanches	1999	<i>Canadian Geotechnical journal</i> , V36, p. 1096-1110
Davies T.R.H., McSaveney M.J.	Dynamic simulation of the motion of fragmenting rock avalanches	2002	<i>Can. Geotech. J.</i> 39, p789-798, 2002
Davies TRH, McSaveney MJ	Runout of Rock Avalanches and volcanic debris avalanches	2003	
Denlinger RP, Iverson RM	Flow of variably fluidized granular masses across three-dimensional terrain 2.Numerical predictions and experimental tests	2001	<i>JGR V.106</i> , p.553-566,2001
Drake TG	Granular flow: physical experiments and their implications for microstructural theories	1991	<i>J. Fluid Mech.</i> , V.225, pp.121-152, 1991
Drake TG	Structural features in granular flows	1990	<i>JGR V:95</i> , p. 8681-8696,1990
Gray JMNT, Hutter K	Pattern formation in granular avalanches	1997	<i>Cotinum Mech. Thermodyn.</i> V.9, p.341-345, 1997
Greve R, Hutter K	Motion of a granular avalanche in a convex and concave curved chute: experiments and theoretical predictions	1993	<i>Phil. Trans. R. Soc. Lond.</i> V.342, p.573-600, 1993
Greve R, Koch T, Hutter K	Unconfined flow of granular avalanches along a partly curved surface. I. Theory	1994	<i>Proc. R. Soc. Lond.</i> V.445, p.399-413, 1994
Koch T, Greve R, Hutter K	Unconfined flow of granular avalanches along a partly curved surface. II. Experiments and numerical computations	1994	<i>Proc. R. Soc. Lond.</i> V.445, p.415-435, 1994
Hsü K. J.	Catastrophic Debris Streams generated by Rockfalls	1975	<i>Geological Society of American Bulletin</i> V.86,I p.129-140, Jan 1975
Hungr O, Morgestern NR	Experiments on the flow behaviour of granular materials at high velocity in an open channel	1984	<i>G V.34</i> , p.405-413, 1984
Hutter K, Koch T	Motion of a granular avalanche in an exponentially curved chute: experiments and theoretical predictions	1991	<i>Phil. Trans. R. Soc. Lond.</i> V.334, p.93-138, 1991
Hutter K, Savage SB	Avalanche dynamics: the motion of a finite mass of gravel down a mountain side	1988	<i>ISL</i> , V.1, p.691-697, 1988
Okura Y, Kitahara H, Sammori T	Fluidization in dry landslides	2000	<i>Engineering geology</i> V.56, p.347-360, 2000
Okura Y, Kitahara H, Sammori T, Kawanami A	The effects fo rockfall volume on runout distance	2000	<i>Engineering geology</i> V.58, p.109-124, 2000
Pouliquen O	Scaling laws in granular flows down rough inclined planes	1999	<i>PF 11</i> , p. 542-547, 1999
Pouliquen O, Fortierre Y	Friction law for dense granular flows: application to the motion of a mass down a rough inclined plane	2002	<i>J.Fluid.Mechanics</i> , V.453, pp.133-151, 2002
Reik G, Hesselmann FJ	A study of kinematic and dynamic aspects of rock slides by means of model tests	1976	<i>Rockfall dynamics and protective works effectiveness. Istituto Sperimentale Modelli E Strutture ISMES</i> , Report n°90, pp. 97-122, 1976
Rengers N, Müller L	Kinematische Versuche an geomechanischen Modellen,	1970	<i>Rock mechanics-Felsmechanik, Suppl.1</i> , p.20-31, 1970
Valentino R., Barla G., Montrasio L.	DEM simulation of dry granular flow in laboratory flume tests	2004	<i>Landslides: Evaluation and Stabilization</i> , V. II, pp. 1489-1495
Wieland M, Gray JMNT, Hutter K	Channelized free-surface flow of cohesionless granular avalanches in a chute with shallow lateral curvature	1999	<i>J.Fluid Mech.</i> V.1999, p.73-100, 1999

3. Action C.2 - Physical modelling: tests description and results

In the following chapters model configuration and tests conditions will be described in details and the results obtained will be listed in a systematic way.

3.1. Experimental set-up and tests description

The model (see figure 3-1) mainly consists of two rectangular panels placed one after the other with a joined side, the first panel is fixed horizontally on the soil and the second one can be positioned at different angle. For the tests shown in this report the inclination has been maintained at 45° degrees. At first place some tests with an inclination of 90° have been made, but as soon as the results obtained have been considered far from reality, this configuration has been abandoned.

During the tests campaign the model has been improved once changing dimensions of certain pieces and some mechanicals parts but maintaining the general configuration.

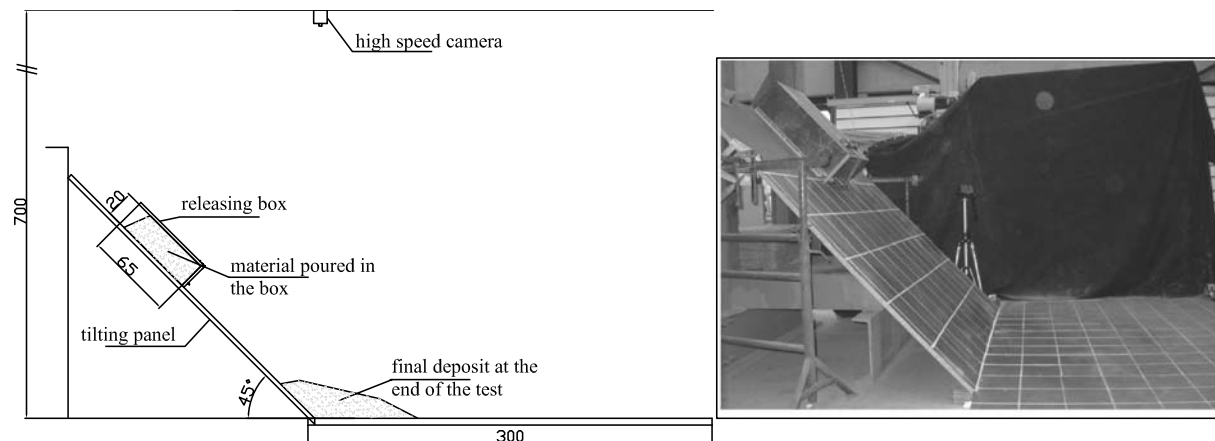


figure 3-1 : the experimental set-up

Tests mainly consist in simulating a rock avalanche dropping different kind of granular material on the panels. Different amounts of material are laid out in a container, a kind of a wood box measuring 20cm height*40cm width*65cm length, placed on the reclining panel. With the use of an elastic rope the box is opened in an almost instantaneous way and the material is released.

Each test is filmed by a digital high speed camera placed at a height of about 7 m from the horizontal panel. In spite of the distance, the films display a residual distortion. A calibration of the camera parameters was operated in order to systematically rectify films obtained.

As already mentioned, even if it is really difficult to match scaling laws, the use of a physical model for this research allows to study the influence of each parameter of interest, controlling and changing one parameter at time and having known and reproducible experimental conditions, contrarily to reality where rock avalanches are isolated and unique phenomena.

Among the various parameters that could affect runout, the proposed research has evaluated by a systematic experimental campaign the influence on the deposit morphology of the following ones:

- nature of released material: Hostun sand (Hs) and two different kind of gravel (Gr2 and Gr4);

- material volume: 10-20-30-40 litres;
- releasing height: 1-2 meters
- releasing geometry (we have changed this parameter placing a separation panel into the box, reducing in this way the opening surface. For most of the tests made the box has an opening surface of 20 cm height*40 cm width and we have reduced it to 20*20, 20*30 and 8.5*40.)
- consecutive releases (for example 30 litres in once or in three releases of 10 litres).

3.2. Measuring devices

Runout, length, height and width of the final deposit have been manually measured after each test. These measurements have been done taking into account only the main part of the deposit, neglecting the band around it formed by a layer of one grain height and where the particles become less and less concentrated.

In literature runout has been considered as the total travel distance between the highest point and the end of the deposit or the distance travelled by the centre of mass. In this case as shown in figure 3-2 runout is the distance travelled by the mass front on the horizontal panel. This choice has been made to have homogeneous results, which depend only on one parameter at a time.

The displacement and the velocity of the mass front on the horizontal panel during the sliding have been evaluated from the film analysis using the software WINalyze. This program is really sensible to differences in contrast. For this reason it has been sometimes difficult to follow the mass front, especially during the experiments with gravel where some particles have travelled out of the main deposit making it difficult to find where this last one ends and leading to a precision of about 5 cm in distances measured.

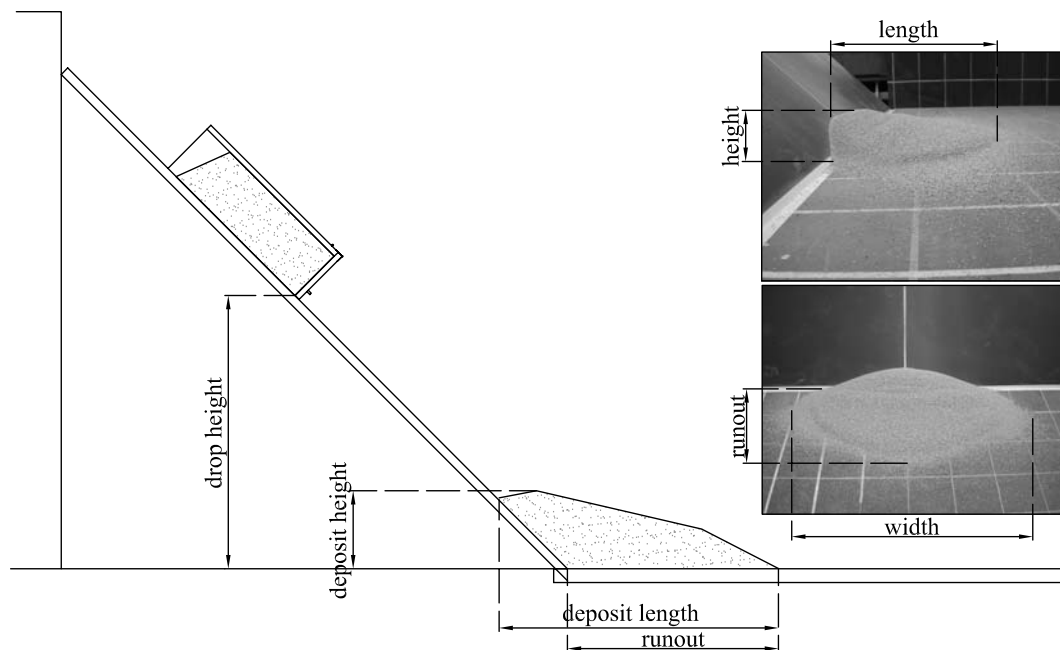


figure 3-2 : in situ measurements

Volume and deposit morphology have been evaluated by means of the fringes projection method. This is an innovative method which is still under development and it requires some additional information that will be given in the following chapter.

Fringes projection method

According to the thesis of Desmangles “Extension of the fringe projection method to large object for shape and deformation measurement (EPFL, 2003)”, the fringe projection method can be divided in three main steps:

1. creation of fringes and their projection on the object surface
2. registration of the object optical print (phase map)
3. retrieval of the height information from the phase map

The necessary instruments are a projector (normally LCD beamers of structured light or lasers are used), a digital camera (with fine quality resolution) and a computer. The projector is used to project the fringes on the object, the camera to take the pictures that are successively elaborated at the computer to retrieve the height information.

It has to be said that in this case the available tools at the institute have been used (camera: Nikon coolpix 4500, projector: EPSON EMP-7250) and measurements have been made with the existing conditions at the laboratory, where luminosity, humidity and temperature were variable and sometimes unfavourable. This has required some more adaptations to obtain good results and an acceptable precision for these tests, but on the other side constitutes a great advantage because it has led to a method which is quite cheap and that can be employed in any situation where a computer, a digital camera and a common beamer are available.

When parallel strips of light (fringes) are projected on an object, if the object is planar the strip will be straight and equispaced, if it is not they will be “distorted and their departure from straightness is related to the shape of the object. ... The period of the fringes cast on the object is modified compared to the period that would be obtained if the structured pattern was projected on a plane (Desmangles)” (see figure 3-3). The shape of the surface is coded in this fringe pattern.

The physical quantity containing the height information is the phase difference between two interfering beams. It is possible to obtain the phase using the intensity I observed in any point of the picture taken. For the tests taken into account in this research the following formula has been used that considered in each point three different intensities resulting by the projection of the same fringes pattern shifted each time of $1/3$ of the period (see figure 3-4).

$$\varphi = \arctan\left(\sqrt{3} \cdot \frac{I_2 - I_3}{2I_1 - I_2 - I_3}\right)$$

In this way the so called “wrapped” phase map is obtained. Afterwards it is necessary to unwrap this map through the “phase-unwrapping”.

Subtracting the phase map of the object (φ_{obj}) and the phase map of what we have chosen to be the reference planar surface (φ_{ref} , where z is considered equal to zero) we can obtain the height of the object by means of the formula:

$$\Delta h = S \cdot \Delta \varphi = S \cdot (\varphi_{obj} - \varphi_{ref})$$

Where S is a factor depending on the set-up geometry.

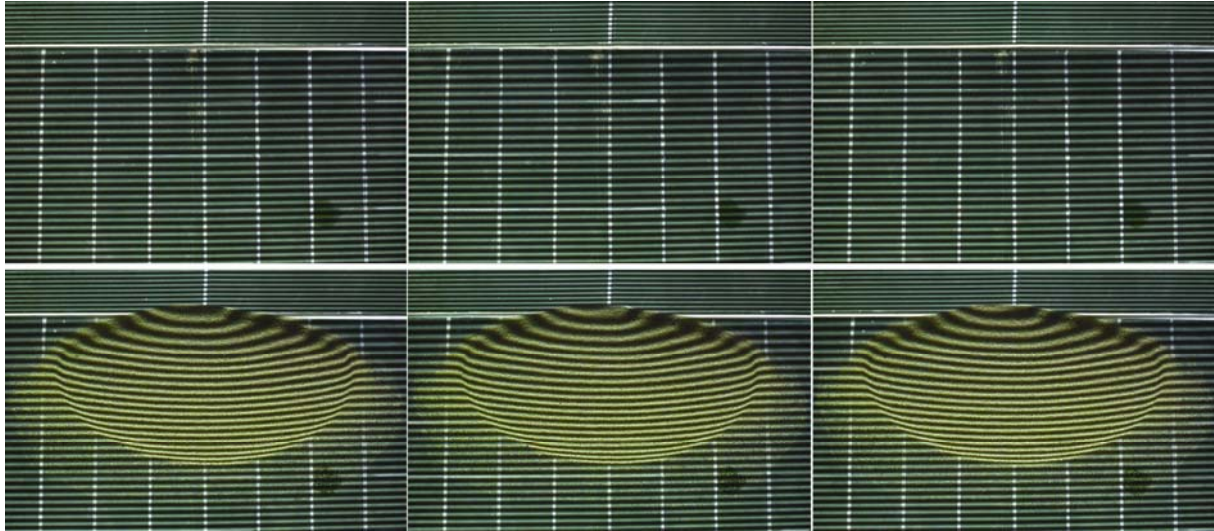


figure 3-3 : pictures used for the phase calculation. On the planar surface and on the object the same fringes are projected each time shifted of 1/3 of the period. The difference between the same fringes pattern projected on a plane and on a granular deposit can be also noticed

This formula has been developed for small objects (order of a few cm) and it is based on the hypothesis that the fringe pattern projected is regular and that the fringes are parallel and equidistant.

As soon as researches in this field are still in progress the fringe projection method is not yet an available and easy to apply method and its employment has required some specific developments. In the case treated here the measurements are on large deposit and a common projector has been used (see figure 3-4) where the illuminating beams are divergent, consequently the fringes are not equidistant as required. It has been decided anyway to use this formula as soon as the precision obtained has been considered acceptable for the purposes of the case: to obtain the shape of the deposit and to have an approximate calculation of the final volume.

In order to obtain the best results with the fringes projection method, the position of the camera and of the projector have been changed, first the pictures were taken from the side, after from above; during the last tests the projector has been placed higher than at the beginning in order to be able to project the light also in the rear part of the deposit, which would have been otherwise in the shadow.

Moreover the set-up geometry changes every-time to be adapted to the object size and the available space and consequently it becomes difficult to calculate the factor S . In order to simplify the calibration, instead using S a factor F has been used that can be more easily obtained for each test and which is equal to the height of the deposit in a specific point measured in situ over the $\Delta\phi$ value on the corresponding point obtained with the calculations.

The precision obtained is of about 5 mm which is in the order of the maximum grains diameter. It has been evaluated, measuring the heights of some points of the deposit with known x and y coordinates and comparing them with the heights calculated with the fringes projection method.

The fully development of this method allow its systematically use in the following part of the research where quantitative interpretation will be carried out. Anyway the errors and the simplifications mentioned above have to be taken into account for a proper use of the data.

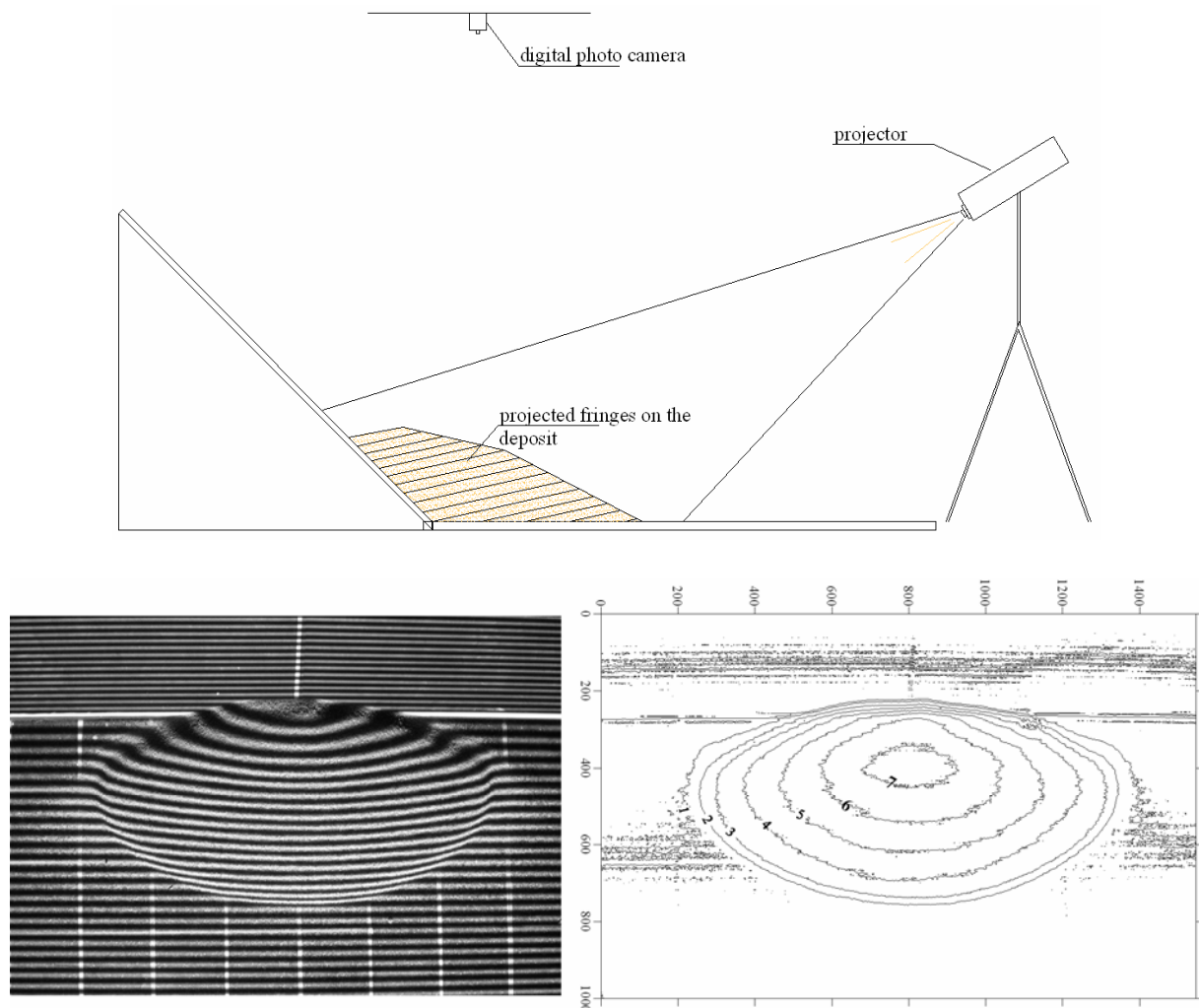


figure 3-4 : fringes projection method set-up and results

Acknowledgements for the development of this method: Professor P. Jacquot, S. Cochard, L.-S. Bieri, M. Pirulli
About the fringes projection method see also:

- Desmangles A.I., (2003): *Extension of the fringe projection method to large object for shape and deformation measurement*. Ph. D. thesis n°2734, Ecole Polytechnique Fédérale de Lausanne, CH
- Lehman M. et al, (1999): *Shape measurements on large surfaces by fringe projection*. Experimental Techniques, Ecole Polytechnique Fédérale de Lausanne, CH, p.31-35
- Bieri L.-S. et al, (2003): *Vision tridimensionnelle par lumière structure appliqué au contrôle qualité en ligne*. SSC Journée d'Etude, Bienne, CH

3.3. Tests programme

Among the series of tests already carried out at the laboratory the following table shows the ones used for the analysis illustrated in this report. The whole list with the measurements done follows in annex.

It has to be mentioned that this programme has been changed in progress with the tests campaign as soon as during an experimental research sometimes even if a test programme has been fixed there are some interesting results which push the researchers to go further in the way indicated by them or sometimes there are problems with the experimental set-up and the measuring devices which lead to some unexpected and sometimes long-lasting changes

Parameters			Material			Height (m)		Volume (l)				Releasing number				Releasing geometry height (cm) * width (cm)			
			Hs	Gr2	Gr4	1	2	10	20	30	40	1	2	3	4	20*20	20*30	20*40	8.5*40
Series number	First model	1A		Gr2		1		10	20	30	40	1						20*40	
		1B		Gr2		1			20	30	40	1	2	3	4			20*40	
		2A	Hs			1		10	20	30		1						20*40	
		2B	Hs			1				30		1	2	3				20*40	
		3A		Gr2		1		10	20			1							8.5*40
		3B		Gr2		1			20			1	2						8.5*40
	Second model	4A		Gr2		1			20	30	40	1						20*40	
		4B		Gr2		1					40	1	2					20*40	
		5	Hs			1			20	30		1						20*40	
		6A		Gr2			2		20	30	40	1						20*40	
		6B		Gr2			2				40	1	2					20*40	
		7	Hs				2			30		1						20*40	
		8			Gr4		2			30		1						20*40	
		9		Gr2			2		20			1				20*20			
		10		Gr2			2		20	30		1					20*30		
		11		Gr2			2		20			1						20*40 flat	

Table 3-1 : tests carried out at the laboratory

The series 1A, 2A, 4A and 5 have been useful to check the experimental set-up when it has been built and when some improvements have been made. As soon as these series have the same test conditions, they have allowed verifying if the model has suffered any changes in the configuration when the modifications have been made.

The series, 1A, 4A, 2A as well as the series 6A have been also used to study the volume influence on the runout and deposit characteristics.

On the other hand the 1B, 2B, 3B, 4B, 6B series have allowed to study the influence of the way a certain volume of material is released, all in once or at different consecutive releases.

The 1A, 2A, 5, 6A, 7 and 8 have underlined the different behaviour of the three granular materials used.

The 4A and the 6A have been used to study the influence of the drop height and finally the 6A, 9, 10 and 11 series have underlined the influence of the releasing geometry.

The objectives of each series will be better enlightened in the chapter 3.5 following the overview on tests results.

3.4.Results interpretation

The carried out experimental campaign has been very helpful for testing the experimental set-up and the measuring devices, and it has led to some interesting conclusions for a better understanding of the rockslide phenomenology and for the definition of the most important parameters, as indicated from the purposes of the project. In the following chapters the qualitative interpretation of the results obtained from visual observation and first analysis will be presented. A paragraph will be dedicated to each parameter varied to systematically analyse its influence on runout, length, width, height and morphology of the final deposit and on the mass front velocity.

More quantitative interpretations will be developed at the LMR during a PhD thesis in progress that follows the INTERREG project.

Granular materials and influence on deposit morphology

The three kinds of granular materials used for the tests are:

- Hs : Hostun sand, a really fine sand
- Gr2 : Aquarium gravel 2, a gravel used for aquarium decoration
- Gr4 : Aquarium gravel 4, also used for aquarium decoration

The main characteristics of these materials are listed on the table 3-2. The unit weight of the material has been measured weighting a bucket of known volume, filled with non- compacted soils.

The Hostun sand shows an abnormal behaviour as its basal friction angle was found to vary in a range between 34° and 40°, which is bigger than its internal friction angle of 34°. In fact as soon as the grains are very fine a thin layer is stopped by the asperities of the panel surface. Consequently the first value (34°) of the range is referred to the moment when an above layer of sand slides on another, the second value (40°) refers to the total departure of the material: this happens only when the thin layer of sand, firstly stopped, also slides.

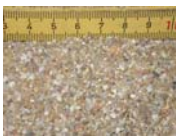
Characteristics		Grains size [mm]	Unit weight [kN/m ³]	Φ_{int}	Φ_{base}	photo
material	Hs	0.315-0.8	12.6	34°	34°-40°	
	Gr2	0.5-3	14.9	33°	32°	
	Gr4	1-4	15.0	37°	30°-32°	

table 3-2 : granular materials characteristics

As mentioned above the tests series used to underline the different behaviour of the materials are 1A, 2A, 5, 6A, 7 and 8 (see figure 3-6, 3-7).

Gr4 has been tested for only one configuration and one volume (series 8). For what concern the measurements slight differences have been noticed between the behaviour of the two gravels: using Gr4 with bigger grains diameter, runout increases of 2% maximum and width remains almost constant; length and height increase of about 9%. Front mass velocity remains almost constant. The morphology of the deposit is similar except for a different shape at the borders, more homogenously rounded at the rear border in the case of Gr4.

The greatest differences can be noticed comparing the tests made with Hostun sand and the ones with gravel aquarium 2. The general trends are similar but the values vary a lot: comparing the deposit heights of the Hostun sand tests with the Gr2 ones a decreasing of even the 50% can be observed. On the other hand using the gravel length, width, runout and front mass velocity increase.

What is really interesting is a clear difference in the deposit morphology (see figure 3-8). The configuration of the sand is in conformity with many experiments described in literature (Hutter, Savage, Bagnold...), while aquarium gravel deposit has well marked angular

discontinuities (central zone with weak slope, but front and rear and side strongly tilted). A similar morphology has been noticed in situ at the Six des Eaux Froides (Valais, Switzerland) and on other rock avalanches deposits (such as the one of Frank Slide, according to statements of Oldrich Hungr).

Among all the experiences reviewed in literature, it has been noticed that most of them are made with sandy materials or with different kinds of beads and gravel is seldom used. Although sands respect the hypothesis of shallow flow made for most of the used numerical models, from these preliminary tests at LMR it comes out that deposit morphology of gravel materials seems nearer to real circumstances.

This difference in morphology results probably more from the shape and the angularity of the grains than from the grain size distribution. This point remains nevertheless to be cleared up in the future. The systematized test of different kinds of gravel and blocks sets can contribute to verify if the observed similarity of these preliminary experiences can lead to a better reproduction of reality and understanding of rockslide runout and can constitute a reliable sample for the validation of forecast models.

For the reasons mentioned above, in the following chapter we will deal only with tests made with Gr2, if not otherwise specified. This material seems definitively more representative and suitable for study purposes.

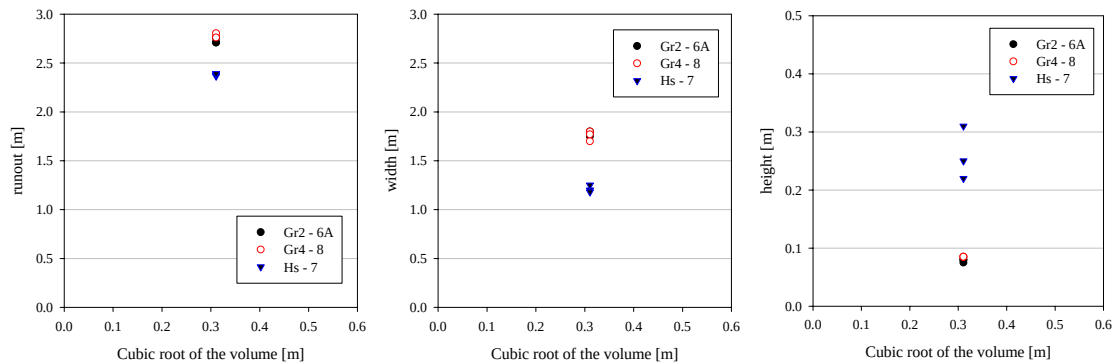


figure 3-5 : comparison between Gr2, Gr4 and HS (30 litres, 2 m drop height, 1 release, box opening 20*40)

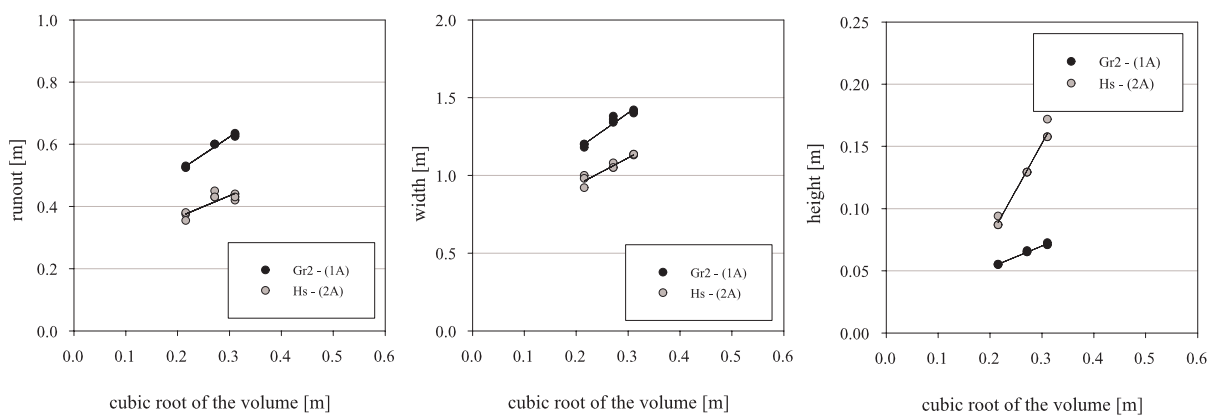


figure 3-6 : comparison between Gr2 and Hs (1 m drop height, 1 release, box opening 20*40)

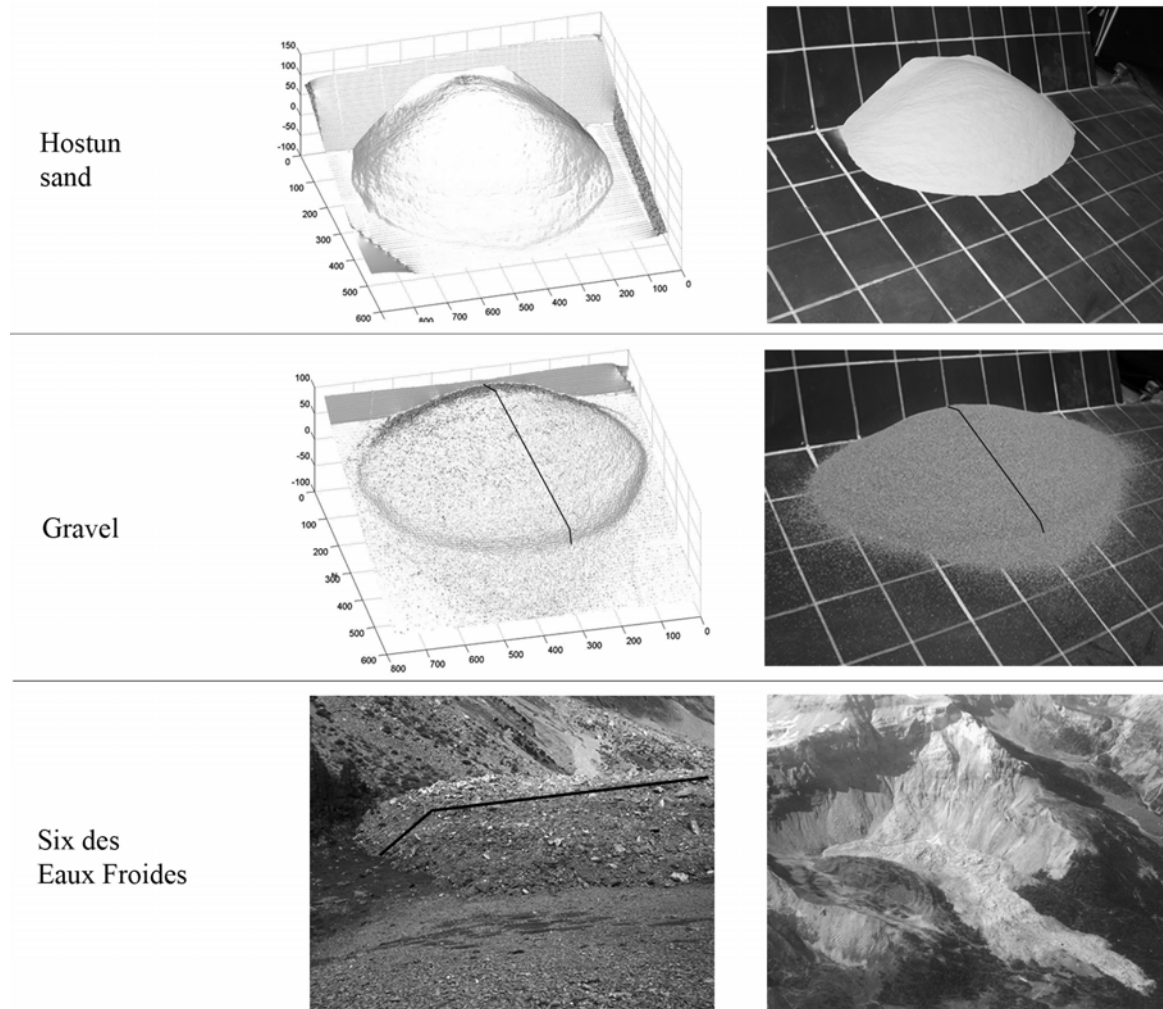


figure 3-7 : influence of material type on deposit morphology

Volume and drop height

Comparing 4A and 6A series, it comes out that the volume of the released material influences the deposit characteristics (see fig.3-8 for width, runout and velocity graphics). Even if it slightly influences deposit morphology, geometry dimensions increase with the increasing of the volume. For what concerns the front velocities, monitored from the high speed camera, they remain quite similar for the different volumes until the mass comes almost to a rest and they only differentiate themselves in the last part of the runout.

It can be thus assumed that the volume has a significant influence only in the last part of the sliding where the rear part of the mass seems to push or to run over the deposit which is already taking shape at the base, maybe with a transfer of linear momentum between the rear part approaching and the front one stopping.

Observing the first graphic at figure 3-8 we can deduce that there is an interaction between the volume and the drop height. Actually it seems that the drop height has less and less influence on the runout with the increasing of the volume. This consideration seems to confirm the theory of Legros (2002) which affirms that the runout distance of large rockslides depends primarily on the volume and not on the fall height.

On the other hand it can be observed an influence of the releasing height on the deposit morphology and on the propagation mechanism: when dropped from 2 meters the mass tends

to a flatter and more spread shape and the entire mass passes over the line between the two panels. This can be due mainly to the fact that in this case the mass potential energy is bigger.

For what concerns the propagation mechanism it can be seen in figure 3-9 that when released from 1 meter the mass seems to follow a triangular propagation with an angle of about 15° , while in the second case, with 2 meters height the mechanism of propagation seems to be composed of two parts, one at the beginning that follows a triangular shape with the same opening angle (about 15°) and a second one which continues almost straight along the deepest slope after the mass front has reached a certain width. When released from 1 metre the mass hasn't enough time and distance to develop this second mechanism.

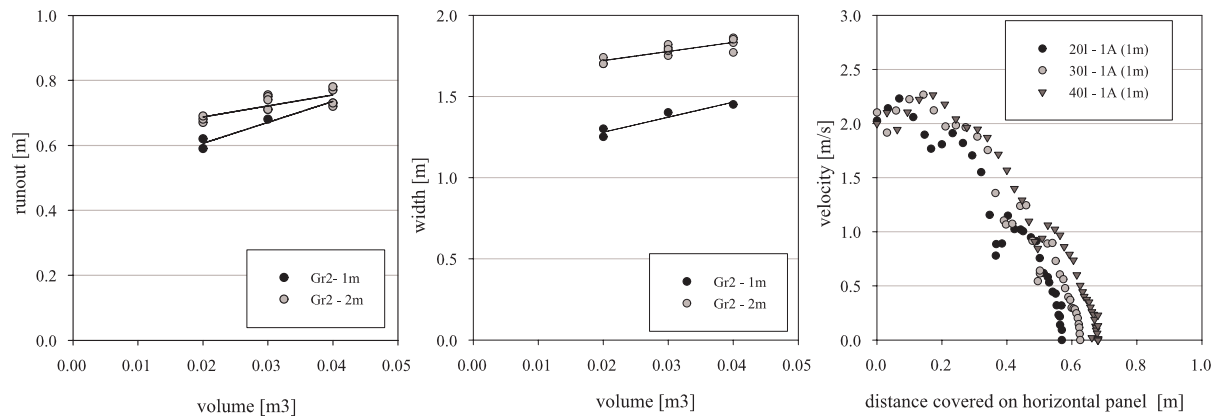


figure 3-8 : volume and height influence (1 release, box opening 20*40)

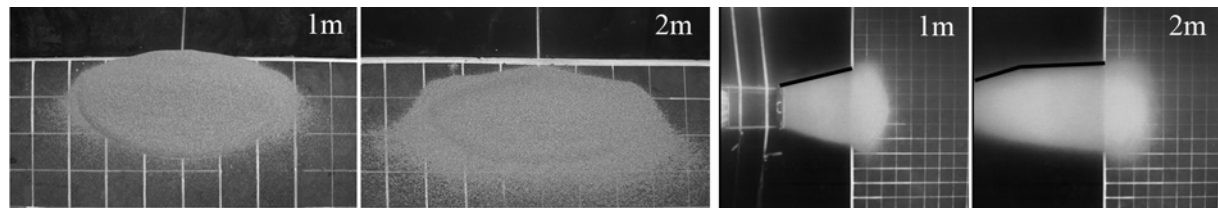


figure 3-9 : difference in final deposit and propagation mechanism for 1 (left) and 2 meters (right) drop height (gr2,40 litres for first two photos, 20 litres for the others, box opening 20*40)

Releasing geometry

As already mentioned, the series 1A and 4A have been useful to verify if the model has suffered any changes when some pieces modifications have been made. Actually there is a difference of about a 5% between the length deposit of the two series. This can be due to the fact that in the two cases the box has been filled up differently leading to a different mass shape before the releasing: for most of the tests, after having filled up the box, the material has been handled trying to create an upper surface of the mass parallel as much as possible to the opening of the box. On the other hand during 4A series the material has been left free to fall down into the box without having the possibility to handle it.

In order to verify this hypothesis the series number 11 has been carried out and it has been compared with number 6A (20 litres). In series 11 the material has been left free to fall into the box without handle it afterwards (indicated by the word flat in table 2 as soon as the mass form in the box is more flattened than usual), while in the 6A one the material has been handled afterwards as usual.

The results obtained seem to confirm that the releasing geometry has an influence on the deposit morphology.

Moreover analysing the influence of volume and releasing height we have noticed that for the deposit characteristics, the regression lines don't pass in the origin of the axes but there is always a positive constant. This could be due to departure geometry. Normally the material has been poured into the box covering the entire surface of the opening part and varying the depth of the filling following the volumes used. In this chapter, using series 6A, 9 and 10, it is analysed if this could have influenced the deposit characteristics.

Changing the opening capacity of the box (20cm height x 20cm width, 20cm height x 30cm width, 20cm height x 40cm width), we have first varied the filling depth maintaining the same volume (20 litres; case b on figure 10) and then we have varied the volume (20l, 30l, 40l) keeping almost the same filling depth (case c on figure 10). In figure 10 the three situations studied are schematically represented, they have been simplified drawing a parallelepiped to represent the mass shape in the box.

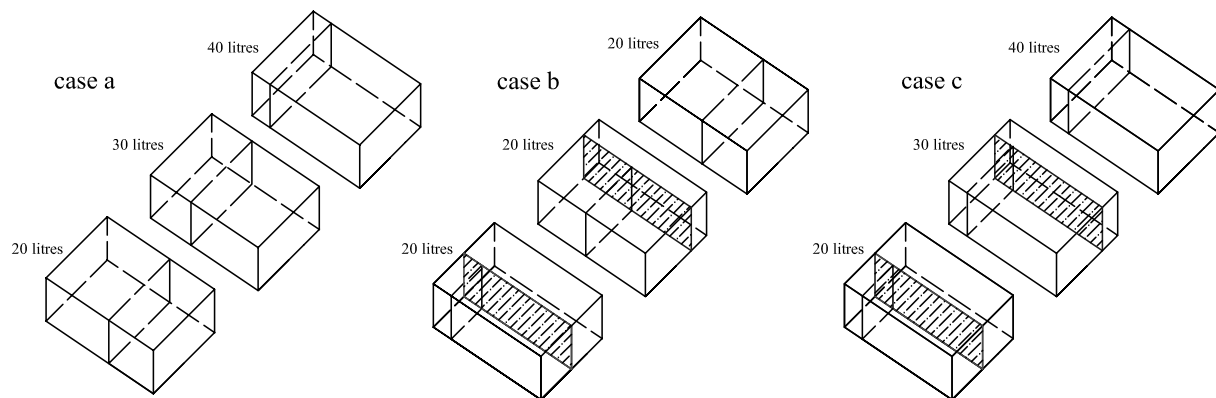


figure 3-10 : Changing in releasing geometry

The results have confirmed more or less the hypothesis made as the departure geometry seems to have an influence, even if variations are of little percentage and sometimes trends are not so clear. The most interesting considerations can be made observing the graphics regarding deposit widths (see fig.11).

Using the same volume and increasing the width (case b) it is possible to notice an increment of the final deposit width too. Otherwise varying the volume and the departure width (case c) also the final deposit width varies of about the same values with which the departure width has been varied.

In some cases the results are too variable to establish a trend and the experiments done are not sufficient to draw some conclusions but they constitute a base for future tests in this sense and a first confirmation of the intuitive hypothesis made.

Anyway it can be assumed that there are some interactions between the two parameters: volume and releasing geometry.

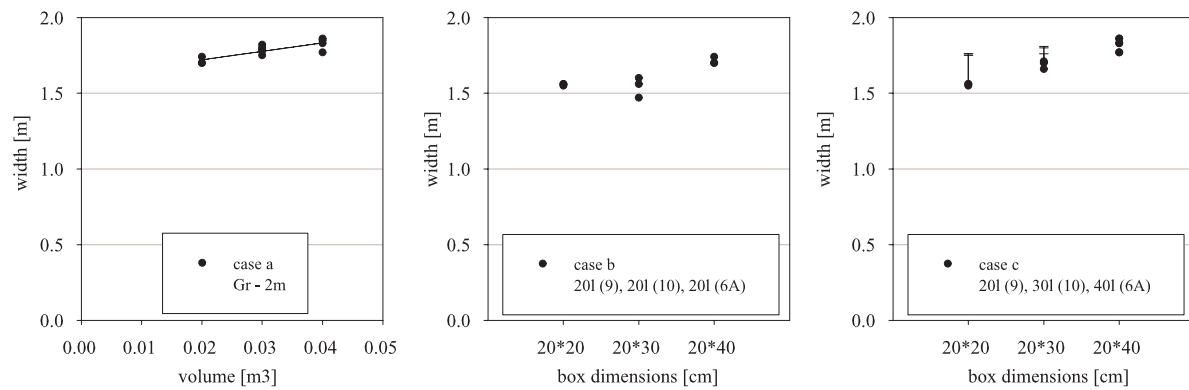


figure 3-11 : Influence of departure geometry dimensions (2 m drop height, 1 release)

Consecutive releases

As already mentioned, to vary the number of consecutive releases means that the considered tests consist in releasing 40 litres:

- in one time (40l)
- in two times (20l over 20l) and
- in four times (10l over 10l over 10l over 10l)

The series analysed here for this purpose are number 1B, 2B, 4B and 6B.

It can be observed that with the increasing of the number of times in which the releasing of a certain volume is divided, deposit length increases moderately, height increases significantly and on the other hand runout decreases (see fig.3-12 and 3-13). Width has a variable behaviour depending on tests configuration.

This behaviour could be explained observing the effects of each release on the development of the deposit characteristics (fig.3-14 and 3-15). It can be noticed that actually is the first release which determines how far the entire volume will travel, the runout being constant all along the test: the following releases are almost stopped by the deposit that has already taken shape at the base and they will develop on the first deposit, increasing mostly in height where the mass has no constraints. As soon as one release is separated from the one that follows, it is not as in the case discussed in the paragraph regarding the volume influence: in that case the deposit at the base was coming to an halt and consequently still in movement and so there was a transfer of linear momentum, in this case the material at the base has completely stopped.

In addition the deposit morphology proved to be very dependent on the number of consecutive releases. In fact when the mass is released in several times, a relatively conical deposit can be observed: as already said above, each consecutive release arranges itself on the deposit formed by the previous one. This kind of behaviour is in agreement with in situ observations, like the rather conical and narrow deposit of the Randa event in the Matter Valley (1991, Swiss Alps) which occurred within several hours. According to Eberhardt (2004) even if the total volume of the mass slide was of 20 million m³ the runout distance was significantly shorter than those seen for other large rockslides of comparable volume: if the slide mass does not fail as a singular event then the potential energy, the mass corresponding momentum and consequently the runout and the characteristics of the final deposit are not a function of the entire failed volume but that of the individual episodic events of smaller volumes.

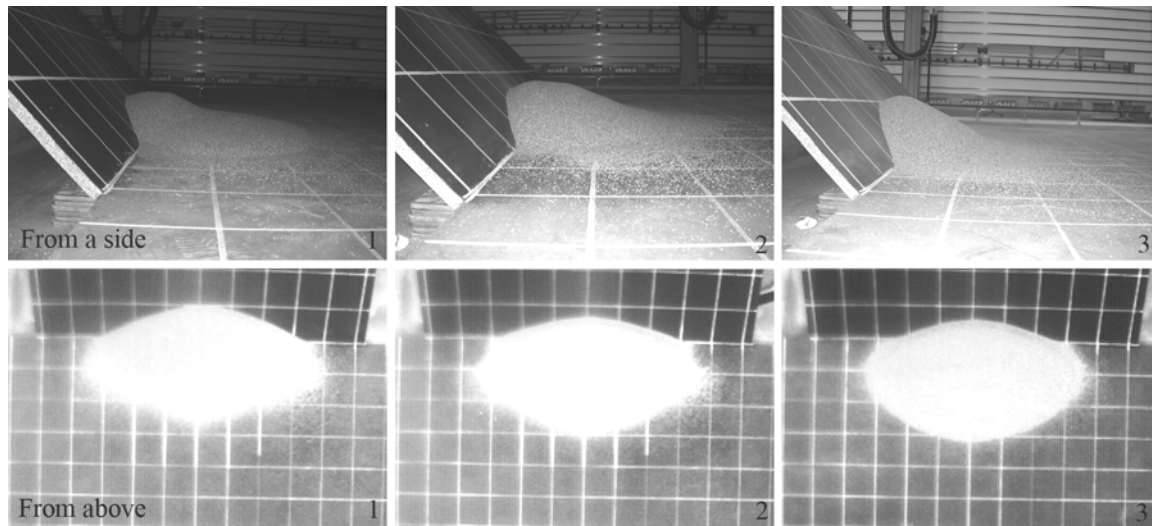


figure 3-12 : Test images: influence of the number of consecutive releases on final deposit (40 litres, 1 m drop height, box opening 20x40)

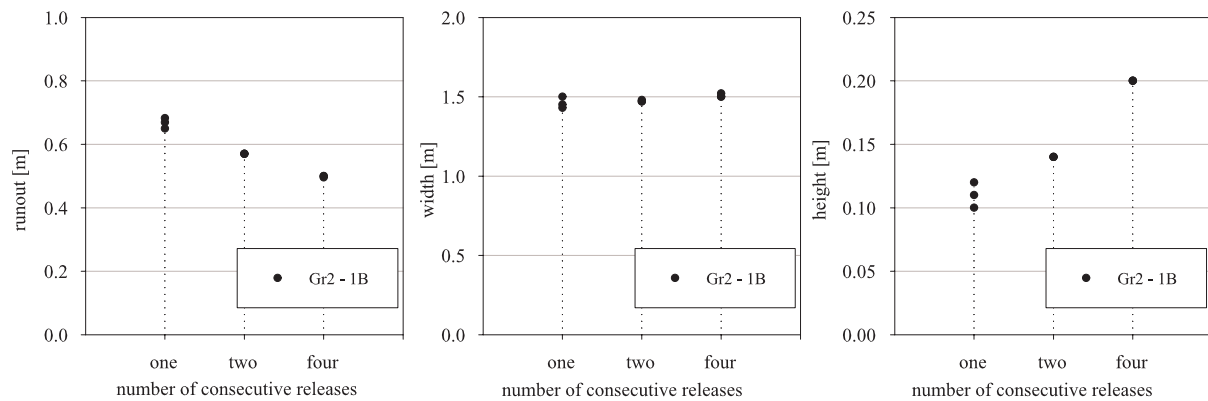


figure 3-13 : Influence of the number of consecutive releases on the final deposit characteristics (40 litres, 1 m drop height, box opening 20x40)

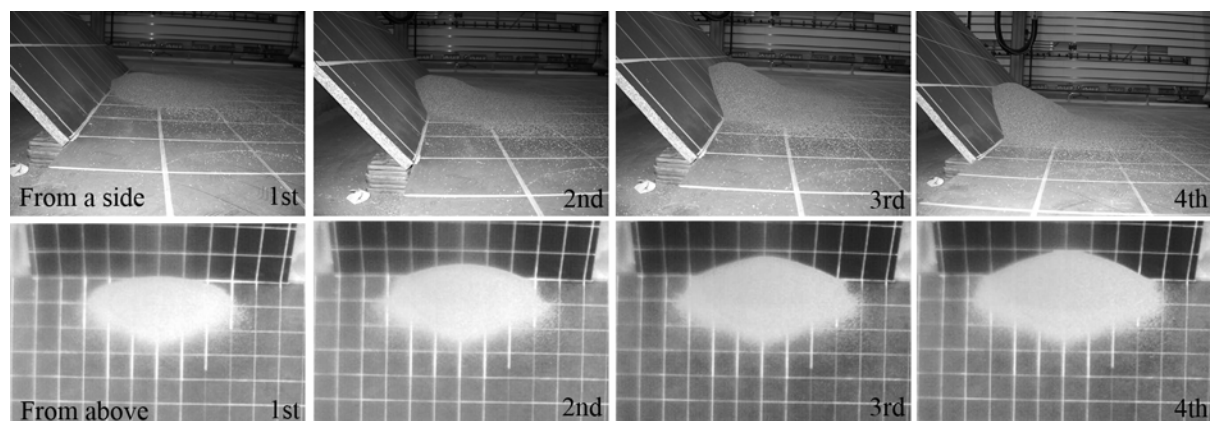


figure 3-14 : Test images: evolution of the deposit with the consecutive releases (10 litres, 1 m drop height, box opening 20x40)

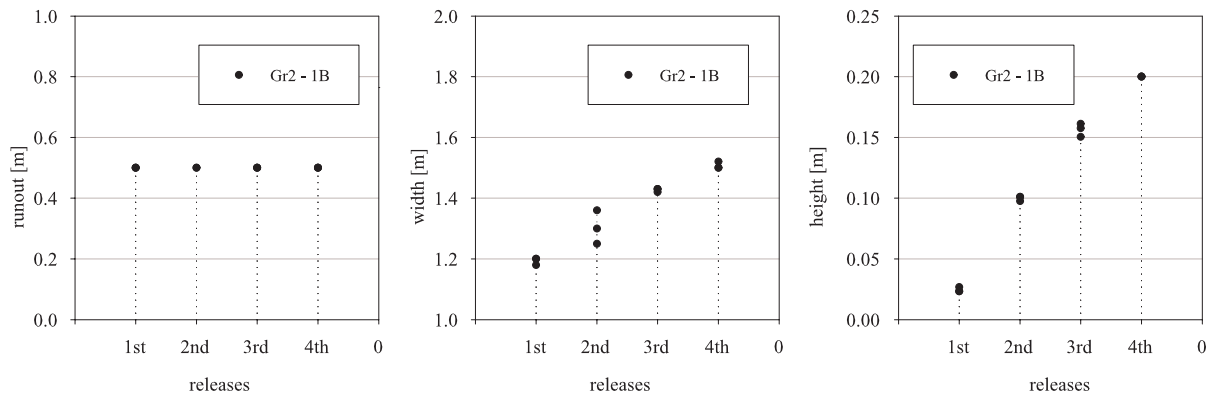


figure 3-15 : Evolution of the deposit characteristics with the consecutive releases (10 litres, 1 m drop height, box opening 20x40)

About the Randa event see also:

- Eberhardt E., (2004): *Numerical analysis of initiation and progressive failure in natural rock slope – the 1991 Randa Rockslide*. International Journal of Rock mechanics and mining sciences, n° 41, p.69-87

Resume table

The following table has the purpose to give the reader a quick view over the qualitative relationship between the different parameters studied, explained above.

The flash indicates:

↗ : increasing of the parameter on the line cause an increasing of the parameter on the corresponding column

↘ : increasing of the parameter on the line cause a decreasing of the parameter on the corresponding column

↔ : increasing of the parameter on the line has almost no effect on the parameter on the corresponding column

Parameter	Runout	Deposit width	Deposit height	Deposit length	Deposit morphology	Mass front velocity
Materials From Hs to Gr2	↗	↗	↘↘	↗	significantly different shape and features	↗
Materials From Gr2 to Gr4	↗ Slightly	↔	↗ Slightly	↗	Same features of the main deposit	↔
Volume	↗	↗	↗	↗	↔	↗ Only at the end
Drop height	↗	↗	↘	↗ Slightly	Different shape but same features	↗ Same behaviour
Releasing width - same volume	↔	↗ slightly	Variable	Variable	↔	↔
Constant releasing depth - different volume	↗	↗	↗	↗	↔	↔
Number of releases	↘	variable	↗↗	↗	Evolution to a conic shape	-
Each consecutive releases	↔	↗	↗↗	↗	-	-

table 3-3 : resume table of qualitative results interpretation

3.5. Conclusions and future developments

Granular flow physical modelling in progress at LMR-EPFL allows to draw some useful conclusions for a better understanding of rockslides phenomena. For the moment, as already mentioned above, the varied parameters have been the following ones:

- nature of released material: Hostun sand and aquarium gravel (Gr2, Gr4);
- material volume: 10-20-30-40 litres;
- releasing height: 1-2 meters;
- releasing geometry (20cm x 40cm, 20x20 and 20x30).
- consecutive releases (for example 30 litres in once or in three releases of 10 litres).

The experiments have emphasised a clear dependency of the deposit morphology on the use of sand or gravel. Sand deposit shape, regular and compact, is in conformity with many experiments described in literature, while aquarium gravel deposit, irregular (a central zone with weak slope, but front and rear and side strongly tilted), is in conformity with deposit characteristics of some real cases and it seems then nearer to real circumstances. The main cause of this different gravel behaviour could be probably found in the shape and the angularity of the grains but these considerations has to be deepened and verified with future tests.

There is also a considerable difference in deposit morphology and dimensions when the event is the consequence of one big volume released at once or when the same volume is released at different times: in this last case the characteristics of the final deposit are not a function of the entire failed volume but that of the individual smaller ones. This kind of behaviour is in agreement with in situ observations, like the rather conical and narrow deposit of the Randa event in the Matter Valley (Swiss Alps) which occurred within several hours.

Analysing the volume and drop height influence on the runout we have noticed that even if an interaction exists between these two parameters, the runout distance depends primarily on the volume and slightly on the fall height.

Two different mechanisms of propagation can be observed when the sliding mass is released: triangular propagation with an opening angle of about 15° first, followed by a translation along the deepest slope. The drop height does influence this propagation as both mechanisms are only observed when the mass is released from 2 metres, while in the 1 metre case the mass reaches the horizontal panel before the second mechanism could develop itself.

Finally, there is a certain dependency of the geometry of the final deposit on that of the departure one, especially for what concerns the width.

It has to be said that these considerations regard only the test conditions considered in this paper. The range of parameters studied and the number of tests carried out are not yet sufficient to generalise them. Consequently they remain to be deepened and cleared up in the future. An improved model has already been built at the LMR to study other parameters which could have an important influence on rockslide runout and which could help to review and widen the results obtained. Among the new factors that are going to be varied with this new experimental set-up there are inclination of the tilting panel, roughness of the basal surface, different kinds of gravel and blocks sets.

Qualitative and quantitative interpretations of the results, use of numerical codes to simulate the tests made and comparison with real cases will contribute to extend these first considerations and to give an inner eye into rockslide phenomena.

4. Action C.2 - Physical modelling: simulation of a test with the different codes

In order to establish (constitute) a base of experimental comparison for the numeric (digital) models of the partners and to validate the codes they use on a unique test, the data of one of the experiment carried out at the laboratory have been furnished to the partners.

The test on which the partners have worked belongs to the series 1A and it has the following characteristics.

Parameters	Material			Height (m)		Volume (l)				Releasing number				Releasing geometry height (cm) * width (cm)			
	Hs	Gr2	Gr4	1	2	10	20	30	40	1	2	3	4	20*20	20*30	20*40	8.5*40
Codes validation test		Gr2		1			20			1						20*40	

A release from 1 m height of 20 litres of Gr2 ($\phi_i=33^\circ$, $\phi_b=32^\circ$).

The creation of the digital terrain model representing the geometry of the model (an inclined plane at 45° degrees and a horizontal plan) as well as the definition of the zone of departure (0.25 m x 0.20 m x 0.4 m box filled with 20 l of granular material) were made by each of the teams, but should not constitute any differences. On the other hand, some data are particular depending on the model used:

- Cemagref used its code for avalanches which is based on a "frictional" model. The friction coefficient used is equal to 0.62 corresponding to the tangent of the friction angle at the base ($\phi_b=32^\circ$). No calibration has been made.
- For the model EPAN3D the released mass was divided in 1911 elementary volumes arranged according to a cubic network in seven (layers). A back-analysis of the laboratory test allowed a calibration of the parameters of the developed constitutive model. The finally retained set is:

γ (kN/m ³)	ϕ_0 (°)	ϕ_1 (°)	V_0 (m/s)	V_1 (m/s)	S_0 (m)	r_f (°)	g_0 (°)	r_g (°)	e_0 (°)	r_e (°)
16.5	11	44.5	0.1	0.5	0.05	0.05	1	0	1	-0.96

- The application of the model RASH3D is also based on a model of the type "frictional". The basal friction angle was fixed at 42° , after calibration on the results of the laboratory test.

4.1. Comparison between the codes results

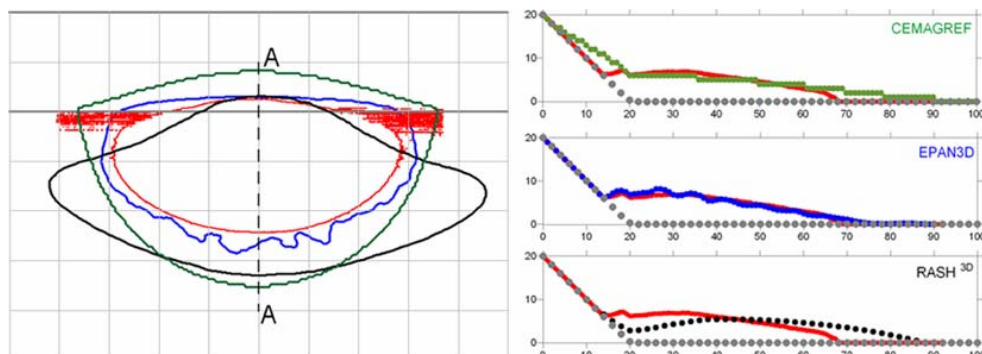


figure 4-1 : Deposit spreading consecutive to the release of 20 litres of gravel since 1 m height. Comparison of the measures (in red) and digital models: C  magref in green, Cete in blue and Politecnico in black. These outlines are drawn for a thickness of 5 mm, not to contain the layer of gravel ($D_{max} = 4$ mm) thrown out the main deposit. Longitudinal section of the observed deposit (red) and modelled deposits, according to the axis AA

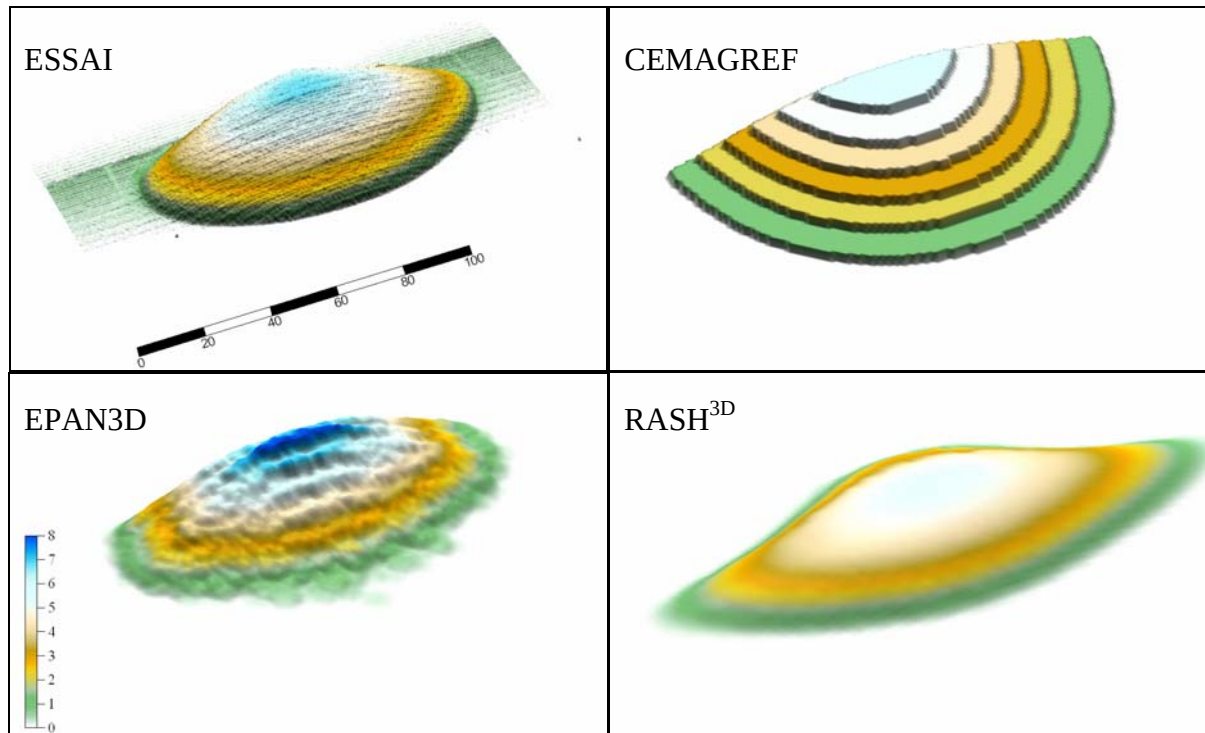


figure 4-2 : 3D view of the observed deposit and the deposits modelled by three partners.

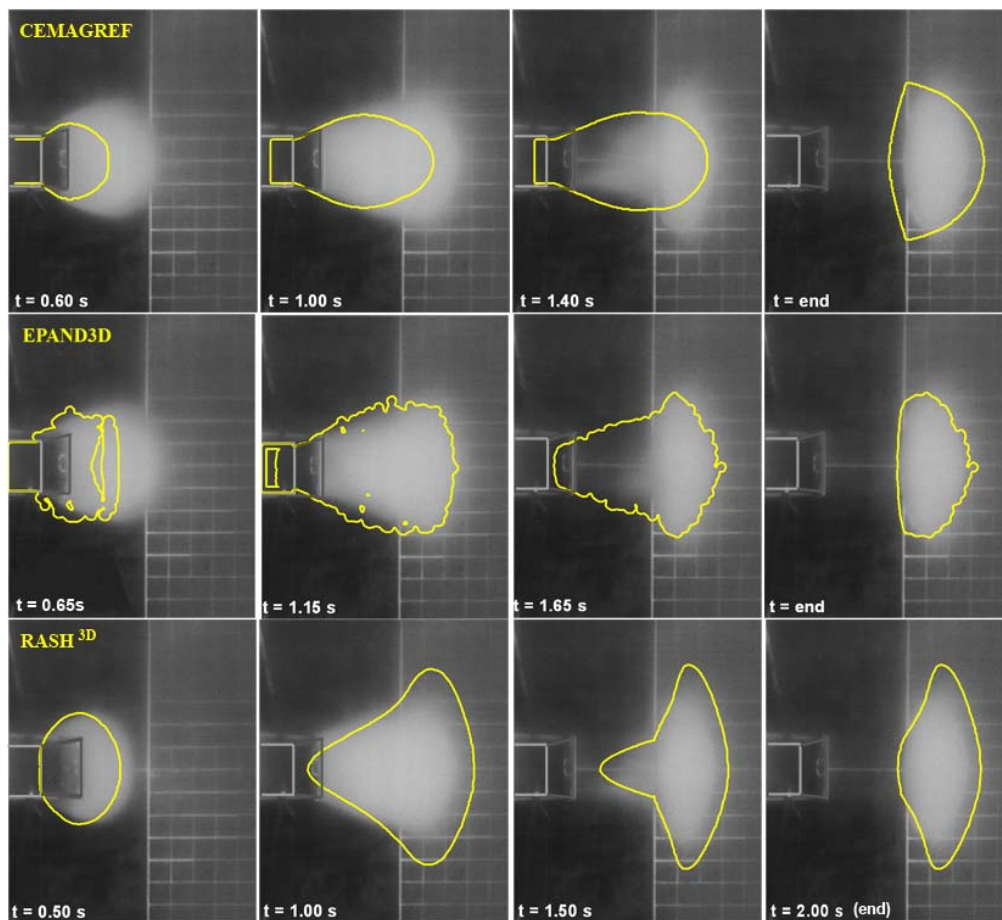


figure 4-3 : Comparison of the mass distribution between the one observed in laboratory (images in background) and the one modelled by three programs of calculation. The outline represented in yellow concerns the 1 mm thickness contours.

The table below compares qualitatively the predictions of three digital models with the observations made during the laboratory test. The symbols +, +/- and - mean respectively good, average, imperfect adequacy, for the characteristic indicated at the head of column.

	Model	Analysis	Propagation		Deposit dimensions			Deposit Morphology		
			Runout	Speed	longitudinal Extension	lateral Extension	Height	General shape	front	rear
Cemagref	‘frictional’	Without calibration	+/-	-	-	+/-	+/-	-	-	-
EPAN3D	11 parameters	Back-analysis	+	-	+	+	+	+	+/-	+
RASH^{3D}	‘frictional’	Back-analysis	+/-	+	+/-	-	+/-	-	+/-	-

Although relatively far away from observations made on the extension and the morphology of the gravel deposit, the results obtained by Cemagref seem completely relevant in term of runout distance, if we take into account that no parameter calibration has been made. Compared to the predictions made by the partners, the results obtained by the model EPAN3D seem the best ones, but they result from a back-analysis and from the calibration of 11 parameters, not all with physical meaning. The calculation made by RASH3D reproduces well the speed of propagation of the rear and the front of the mass, but less indeed the final deposit in particular in the transversal direction. Besides, the chosen angles of friction are far from the experimental values.

As soon as only one release has been used for this work of comparison of the codes, it is important to put in perspective the above-mentioned reports. Only a comparison among several test configurations would allow a proper analysis.

Annex 1: Data sheet

Parameters		Material			Height (m)		Volume (l)				Releases number				Releasing geometry height (cm) * width (cm)				Measurements(cm)		
		Hs	Gr2	Gr4	1	2	10	20	30	40	1	2	3	4	20*20	20*30	20*40	8.5*40	Length	Height	Width
Series	1st model	1A		Gr2			10				1						20*40		55.0	2.3	120.0
		1A		Gr2			10				1						20*40		54.0	2.3	120.0
		1A		Gr2			10				1						20*40		55.0	2.7	118.0
		1A		Gr2				20			1						20*40		66.0	6.2	134.0
		1A		Gr2				20			1						20*40		65.0	5.1	136.0
		1A		Gr2				20			1						20*40		65.0	5.1	138.0
		1A		Gr2					30		1						20*40		73.0	9.0	140.0
		1A		Gr2					30		1						20*40		71.0	9.0	141.0
		1A		Gr2					30		1						20*40		71.0	8.3	142.0
		1A		Gr2						40	1						20*40		78.0	12.0	150.0
		1A		Gr2						40	1						20*40		77.0	11.0	143.0
		1A		Gr2						40	1						20*40		75.0	10.0	145.0
		1B		Gr2				20				2					20*40		63.0	10.0	125.0
		1B		Gr2				20				2					20*40		63.0	10.0	130.0
		1B		Gr2				20				2					20*40		62.0	9.5	136.0
		1B		Gr2					30				3				20*40		68.0	15.0	143.0
		1B		Gr2					30				3				20*40		68.5	15.5	142.0
		1B		Gr2					30				3				20*40		68.5	16.0	143.0
		1B		Gr2						40		2					20*40		74.0	14.0	147.0
		1B		Gr2						40		2					20*40		73.5	13.5	147.0
		1B		Gr2						40		2					20*40		73.5	13.5	140.0
		1B		Gr2						40				4			20*40		73.0	20.0	150.0
		1B		Gr2						40				4			20*40		73.0	20.0	152.0
		1B		Gr2						40				4			20*40		72.5	20.0	150.0
		2A	Hs				10				1						20*40		47.0	9.4	100.0
		2A	Hs				10				1						20*40		46.5	8.7	98.0

2nd model	2A	Hs		1	10		1		20*40	44.0	8.7	92.0
	2A	Hs		1		20	1		20*40	56.0	12.9	105.0
	2A	Hs		1		20	1		20*40	58.0	12.9	108.0
	2A	Hs		1		20	1		20*40	56.0	12.9	105.0
	2A	Hs		1		30	1		20*40	59.0	17.2	113.5
	2A	Hs		1		30	1		20*40	60.0	15.8	113.0
	2A	Hs		1		30	1		20*40	59.0	15.8	113.5
	2A	Hs		1		30	1		20*40	59.0	15.8	113.0
	2B	Hs		1		20	2		20*40	55.0	17.9	109.0
	2B	Hs		1		20	2		20*40	55.0	16.8	108.0
	2B	Hs		1		20	2		20*40	53.0	16.8	108.5
	2B	Hs		1		30	3		20*40	61.5	24.1	126.0
	2B	Hs		1		30	3		20*40	61.5	23.4	127.0
	2B	Hs		1		30	3		20*40	59.5	23.4	127.0
	3A	Gr2		1	10		1		8.5*40	50.0	4.0	110.0
	3A	Gr2		1		20	1		8.5*40	62.0	6.5	128.0
	3A	Gr2		1		20	1		8.5*40	60.0	6.0	125.0
	3B	Gr2		1		20	2		8.5*40	56.0	10.0	120.0
	4A	Gr2		1		20	1		20*40	62.0	8.5	125.0
	4A	Gr2		1		20	1		20*40	59.0	8.5	130.0
	4A	Gr2		1		20	1		20*40	58.0	7.5	130.0
	4A	Gr2		1		30	1		20*40	68.0	11.0	140.0
	4A	Gr2		1		40	1		20*40	73.0	12.0	145.0
	4B	Gr2		1		40	1	2	20*40	68.0	18.5	144.0
	5	Hs		1		20	1		20*40	49.0	11.0	97.0
	6A	Gr2		2		20	1		20*40	67.0	6.5	174.0
	6A	Gr2		2		20	1		20*40	68.0	6.2	170.0
	6A	Gr2		2		20	1		20*40	69.0	6.5	170.0
	6A	Gr2		2		30	1		20*40	71.0	7.5	175.0
	6A	Gr2		2		30	1		20*40	75.5	8.0	178.0
	6A	Gr2		2		30	1		20*40	71.0	8.0	180.0
	6A	Gr2		2		30	1		20*40	75.0	7.5	182.0
	6A	Gr2		2		30	1		20*40	74.0	8.5	179.0

6A		Gr2		2		40	1			20*40	72.0	8.5	177.0
6A		Gr2		2		40	1			20*40	73.0	9.0	183.0
6A		Gr2		2		40	1			20*40	77.0	9.0	186.0
6A		Gr2		2		40	1			20*40	78.0	9.2	185.0
6B		Gr2		2		40		2		20*40	76.0	11.0	140.0
6B		Gr2		2		40		2		20*40	84.0	15.5	154.0
6B		Gr2		2		40		2		20*40	79.0	13.5	162.0
7	Hs			2		30	1			20*40	66.5	25.0	120.0
7	Hs			2		30	1			20*40	60.5	22.0	118.0
7	Hs			2		30	1			20*40	64.0	31.0	125.0
7	Hs			2		30	1			20*40	62.6	21.2	116.0
8		Gr4		2		30	1			20*40	77.0	8.5	170.0
8		Gr4		2		30	1			20*40	82.0	8.5	180.0
8		Gr4		2		30	1			20*40	78.0	8.5	177.0
8		Gr4		2		30	1			20*40	82.0	8.5	183.0
8		Gr4		2		30	1			20*40	80.0	8.5	189.0
8		Gr4		2		30	1			20*40	76.0	7.5	174.0
9	Gr2			2		20	1			20*20	66.0	6.4	156.0
9	Gr2			2		20	1			20*20	66.0	6.0	155.0
9	Gr2			2		20	1			20*20	66.0	6.0	156.0
10	Gr2			2		20	1			20*30	66.0	6.4	156.0
10	Gr2			2		20	1			20*30	66.0	6.0	155.0
10	Gr2			2		20	1			20*30	66.0	6.0	156.0
10	Gr2			2		30	1			20*30	66.0	6.4	156.0
10	Gr2			2		30	1			20*30	66.0	6.0	155.0
10	Gr2			2		30	1			20*30	66.0	6.0	156.0
11	Gr2			2		20	1			20*40 plat	58.0	7.2	168.0
11	Gr2			2		20	1			20*40 plat	65.0	7.2	160.0
11	Gr2			2		20	1			20*40 plat	64.0	7.0	160.0