Experiments on substratum roughness, grainsize and volume influence on the motion and spreading of rock avalanches

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2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
The main objective of the research is to link granular physics with the modelling of rock avalanches. Laboratory experiments consist to find a convenient granular material, *i.e.* grainsize and physical behaviour, and testing it on simple slope geometry. When the appropriate sliding material is selected, we attempted to model the debris avalanche and the spreading on a slope with different substratum to understand the relationship between the volume and the reach angle, *i.e.* angle of the line joining the top of the scar and the end of the deposit. For a better understanding of the mass spreading, the deposits are scanned with a laser scanner. Datasets are compared to see how the grain size and volume influence a debris avalanche. The relationship between the roughness and grainsize of the substratum shows that the spreading of the sliding mass is increased when the roughness of the substratum starts to be equivalent or greater than the grainsize of the flowing mass. The runout distance displays a more complex relationship, because a long runout distance implies that grains are less spread. This means that if the substratum is too rough the distance diminishes, as well if it is too smooth because the effect on the apparent friction decreases. Up to now our findings do not permit to validate any previous model (Melosh, 1987; Bagnold 1956).

1 INTRODUCTION

Rock avalanches are catastrophic events in which granular masses of rock debris flow at high speeds, commonly with unusually runout distance (Friedmann et al., 2003). A great volume of material (>10^6 m^3) is involved and they can reach high velocities (up to 100 m/s), covering areas over 0.1 km^2. They are costly in term of human life losses and can have consequent impact in the environmental and the economic system. These events are widely studied but not well understood. The aim of this study is to propose a new approach allowing a better understanding how the grainsize, volume and substratum influence the motion and the spreading of rock avalanches. In this paper, we present the preliminary results and observations of our experiments.

2 METHODOLOGY

2.1 Description of the installation

Experiments were performed on an inclined plane of variable angle (Figure 1). On the slope, plaques with different roughness can be clipped to simulate different substratum roughness. The sliding volume is enclosed in a box at the top with a fast opening trap. When the trap opens, the mass is released along a 50 cm long slope and deposits on a 92 cm horizontal plane. The width of the installation is 50 cm.

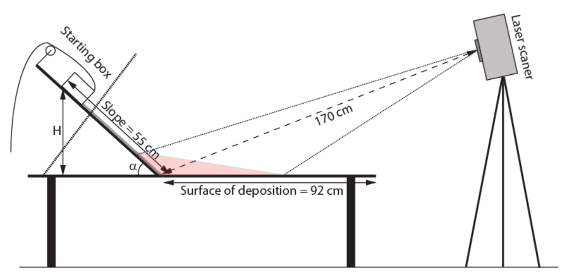

Figure 1. Scheme of the installation with H = height of fall and α = slope angle. The area scanned by the microlidar is represented in transparent.

The deposit is scaned with a laser scaner (Minolta) and the resulting image is a high precision point cloud. By superposition of different datasets, the comparison of how the deposit varies with volume, grainsize and roughness is possible. Finally, pictures of the deposits are taken to analyse the distribution of the blocks.

Experiments were carried out with calibrated carborundum sand. The advantage to use a calibrated material is to know precisely the size of the grains and observe how the grainsize influences the propagation. Our experiments were carried out with five different grainsize ranging from coarse to fine grain (Table 1). The density of the carborundum is 3.21 g/cm^3.

Table 1. Descritption of the used grainsizes.

Grainsizes	Size (mm)
F10	2.83 – 2.38
F16	1.41 – 1.19
F36	0.59 – 0.5
F60	0.297 – 0.25

F120	0.125 – 0.105

To simulate different substratum of the slope, different carborandum sandpapers ranging from coarse to fine grain were used (Table 2). For the deposition surface, wood and sandpaper were used to see how influences on the horizontal motion and the deposition of the mass.

Table 2. Description of the sandpapers used to simulate the roughness of the substratum.

Sandpaper	Particule size (mm)
40	0.425
100	0.140
600	0.016

2.2 Variables

The numbers of variables involved during such complex phenomena is large. To simplify the model, the most important ones are taken into account. The Fahrböschung angle (Eq. 1 and Figure 2), defined by Heim (1932), is the angle of a straight energy line that expresses the rate of frictional dissipation energy (Hsü 1978). The Fahrböschung or apparent coefficient of friction (Φ in Figure 2) is the angle between the horizontal and the line connecting the crown of the head scarp with the most distal end at the toe of the deposit (Pudasaini and Hutter, 2007) and can be expressed as follows (after Heim, 1932):

$$\Phi = \tan^{-1}(H/L) \qquad [1]$$

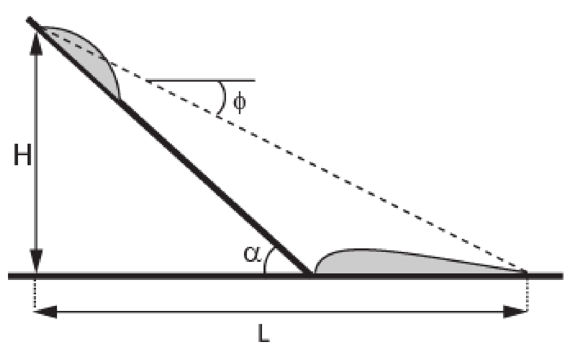

Figure 2. Simplified scheme representing the Fahrböschung (Φ), the runout (L) and the height of fall (H) (modified after Heim, 1932).

Several authors (Scheidegger, 1973; Hsü, 1975; Davies, 1982; Corominas, 1996) have highlighted a strong correlation between coefficient of friction, H/L, and the volume. Indeed, their ratio diminished when the volume increase. After Pollet et al. (2002), the H/L value is generally below 0.6 for large rock avalanches, between 0.1 and 0.4 (corresponding to an apparent coefficient of friction comprise between 6° and 22°). The used variables are summarized in the Table 3.

Table 3. Details of the used variables

Variables	Units	Abreviation
Slope	Degree (°)	α
Fall height	Centimeter (cm)	H
Volume	Cubic centimeter (cm^3)	V
Runout distance	Centimeter (cm)	L
Fahrböschung	Degree (°)	Φ

3 RESULTS

3.1 Influence of the substratum and the grainsize

To observe the influence of the substratum on a moving mass, the experiment was divided into two phases. Initially, the three different substratums (40, 100 and 600) were used on the slope keeping the surface of deposition as wood. For these experiments, five different grainsizes were used with a slope angle fixed at 40°, the height of fall at 35 cm and the volumes were 50 cm^3. The different results are summarized in the Table 4.

Table 4. Results for the simulation of the influence of the subustratum and grainsizes for a slope angle of 40°.

Gsize	Substratum 40			Substratum 100			Substratum 600		
	L (cm)	H/L (-)	Φ (°)	L (cm)	H/L (-)	Φ (°)	L (cm)	H/L (-)	Φ (°)
F10	56	0.63	32.0	55	0.64	32.5	55	0.64	32.5
F16	54	0.65	32.9	56	0.63	32.0	56	0.63	32.0
F36	53	0.66	33.4	56	0.63	32.0	56	0.63	32.0
F60	54	0.65	32.9	56	0.63	32.0	57	0.61	31.6
F120	51	0.69	34.5	53	0.66	33.4	51	0.69	34.5

The results show that the runout distance is greater for coarse grains (F10) than for the finer grains (F120) and that for the three substratums used. The Fahrböschung ranges between 32° and 34.5° for all the experiments and the coefficient of friction ranges between 0.63 and 0.69.
Figure 3 represents the interpolated point clouds of all deposits. The Figure 3a shows the different shapes of the deposits for the coarser substratum 40, the Figure 3b for the substratum 100 and finally the Figure 3c corresponds to the substratum 600. In all these three figures, the coarse grainsize F10 that goes the further and the finer grainsize F120 remains the closer of the slope. We can also observe that the intermediate grainsizes (F16, F36 and F60) go further when the roughness of the substratum diminishes. The observations based on the lidar data are coherent with the results in Table 4.

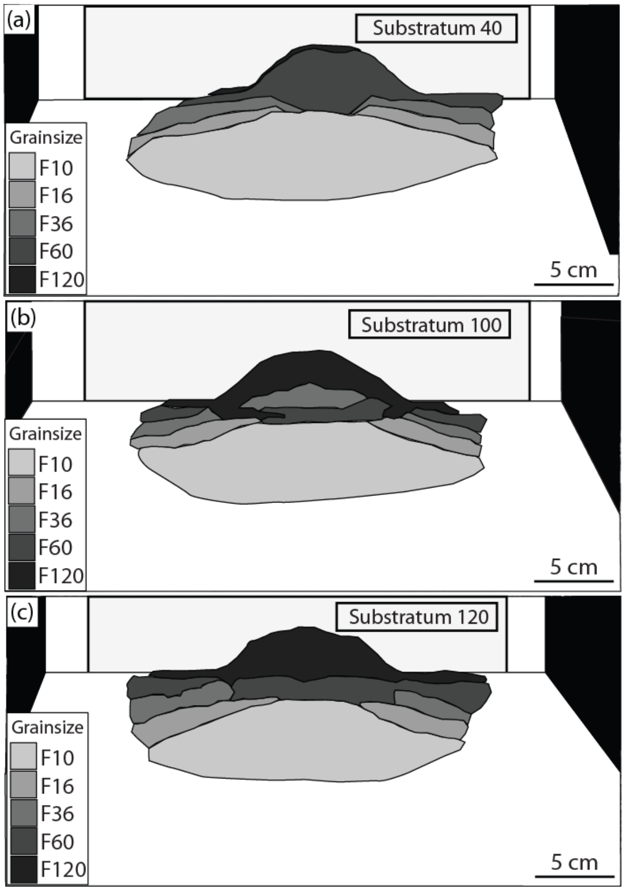

Figure 3. Superposition of the point clouds of the deposits formed by the different grainsizes for (a) the substratum 40 (0.425 mm), (b) 100 (0.146 mm) and (c) 600 (0.016 mm). The surface of deposition is in wood (view from the laser scanner position).

In the second set of tests, a substratum on the surface of deposition was added to see how the roughness influences the deposition of mass. For these experiments, we used only the two extreme substratums (40 and 600) for the five grainsizes. The slope angle was fixed at 40°, the height of fall at 39 cm and the volumes were 50 cm^3. The different results are summarized in the Table 5.

Table 5. Results for the simulation of the influence of the subustratum of the slope and the surface of deposition for a slope angle of 40°.

	Substratum 40			**Substratum 600**		
Gsize	L (cm)	H/L (-)	Φ (°)	L (cm)	H/L (-)	Φ (°)
F10	52	0.67	33.9	58	0.6	31.1
F16	51	0.69	34.5	55	0.64	32.5
F36	49.5	0.71	35.3	51	0.69	34.5
F60	48	0.73	36.1	49	0.71	35.5
F120	47	0.74	36.7	47	0.74	36.7

The results show that the runout distance is greater for the coarse grainsize (F10) than for the finer (F120). The Fahrböschung ranges between 31.1° and 36.7° for all the experiments and the coefficient of friction ranges between 0.6 and 0.74. In comparison with the results get in the Table 4, the results are higher.

Figure 4 represents the interpolated point cloud for the deposits of the grainsize F10 for the two substratums. The shape of the deposit is slightly the same for both experiments but that the deposit with the finer substratum reaches a greater distance than the one with the coarse substratum.

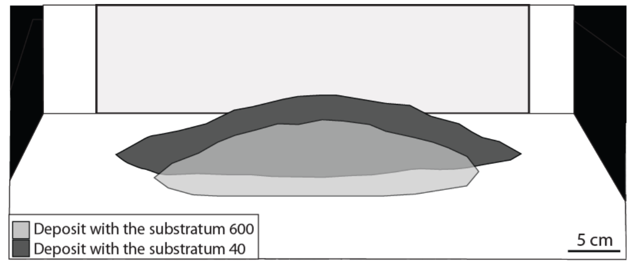

Figure 4. Superposition of the point clouds for the deposits formed by the grainsize F10 for the substratum (slope and surface of deposition) of 40 (0.425 mm) (dark grey) and 600 (light grey) (view from the laser scanner position).

3.2 Influence of the slope angle

Tto observe the influence of the slope, the plane was tilted with an angle of 60°. The three different substratums (40, 100 and 600) were used on the slope while the surface of deposition is in wood. For these experiments, only three different grainsizes were used: the coarser one (F10), the middle one (F36) and the finer one (F120). The height of fall at 35 cm and the volumes were 50 cm^3. The different results are summarized in the Table 6.

Table 6. Results for the simulation with a slope angle of 60°.

	Substratum 40			Substratum 100			Substratum 600		
Gsize	L (cm)	H/L (-)	Φ (°)	L (cm)	H/L (-)	Φ (°)	L (cm)	H/L (-)	Φ (°)
F10	54	0.88	41.4	56	0.85	40.4	53	0.90	41.9
F36	56	0.85	40.4	57	0.84	39.9	59	0.81	38.9
F120	53	0.90	41.9	56	0.85	40.4	56	0.85	40.4

In this experiment, the grainsize reaching the highest travel distance is the medium one, F36. The Fahrböschung ranges between 38.8° and 41.9° for all the experiments and the coefficient of friction ranges between 0.81 and 0.90. These results are significantly higher than those obtained with a slope of 40° (Table 4) meaning that the travel distance is less important when the slope angle is higher.

Figure 5 represents the comparison of the deposits of the grainsize F10 on a substratum 600 for an inclination of 40° and 60°. The shape of the deposit is the same but the mass goes further with a 40° slope.

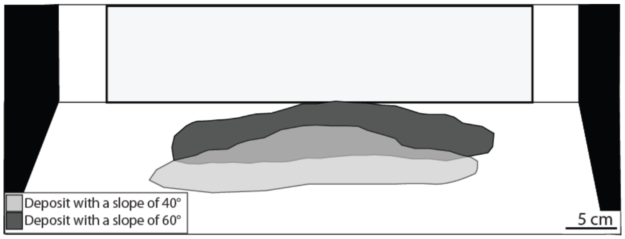

Figure 5. Superposition of the point clouds for the deposits formed by the grainsize F10 for the substratum 40 (0.425 mm) for a slope angle on 40° (light grey) and 60° (dark grey). The surface of deposition is in wood (view from the laser scanner position).

3.3 Influence of the volume and mixed grainsize

To see the influence of the volume and the size of the material, three different grainsize with different volumes were mixed. Three tests were performed with the substratum 100 at a slope angle of 45° and a height of 39 cm. For the tests (a) and (b), a coarse (F10), a medium (F36) and a fine (F120) grainesize were used while for the test (c) the three coarser grainsizes (F10, F16 and F120) were used. The different volumes and the results are summarized in the Table 7.

Table 7. Results for the simulation of the influence of the volume and mixed grainsizes for a slope angle of 45°.

	Volumes of grainsizes					Substratum 100		
	F10	F16	F36	F120	total	L	H/L	Φ
tests	(cm^3)	(cm^3)	(cm^3)	(cm^3)	(cm^3)	(cm)	(-)	(°)
(a)	15	-	28.6	48.8	92.4	51.7	0.75	37.0
(b)	6	-	12.3	27.7	46	53.2	0.73	36.2
(c)	16.3	25.6	52.6	-	94.5	51.6	0.75	37.0

The results show that the smaller volumes, 46 cm^3, that have a greater runout distance, 53.2 cm. The Fahrböschung ranges between 36.2° and 37° and the coefficient of friction ranges between 0.73 and 0.75.

To see if the stratification plays influences the final deposit, three different dispositions of the grainsize in the starting box were tested. For the test (a), grainsizes were stratified in a normal grading before it was put in the starting box resulting in an inverse grading in the box. For the test (b), the grainsizes were homogenously mixed. For test (c), the grainsizes were stratified directly in the starting box in a normal grading. The Figure 6 shows the three deposits. In the Figure 6a and Figure 6b, the two deposits present the same shape with a main body surrounded by a splash area and that the grains tend to organize themselves following the same scheme. In both cases, the finer grainsize F120 forms the lateral extensions of the splash and the top of the mass. The medium grainsize, F36, forms most of the splash area but is less present in the top of the mass. The coarse grainsize, F10, forms the splash area in the front of the mass and is present in the top of the mass but are not present on the side of the deposit. The fact that the medium graisize is not very present at the surface of the deposit indicates that it forms the main inner part of the mass. The Figure 6c shows the last test but the grainsizes are too similar for being well identified in the picture. The shape of the deposit is significantly different. In fact, the lateral extend of the deposit is better constrained and the coarse grainsize (F10) tends to concentrate on the both sides of the mass. The splash is mainly formed by the grainsize F10 and F36 but only a few grains of F16 are presents. As the two previous cases, the medium grainsize probably forms the inner part of the mass.

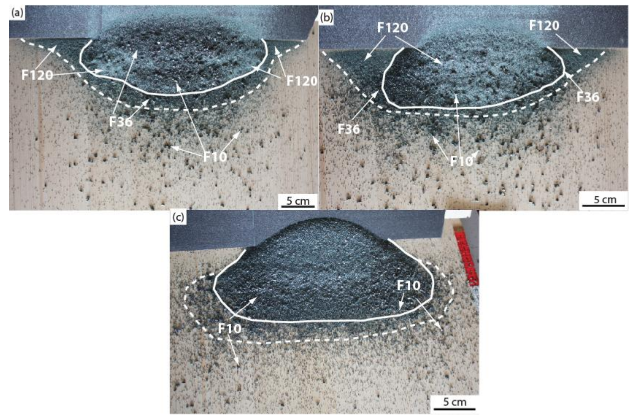

Figure 6. Deposits for a volume of 92.4 cm^3 (a), 46 cm^3 (b) and 95.4 cm^3 (c). The area enclosed by the full line is the main mass ant the splash area is enclosed by the dashed line. Note that not all the grains are enclosed by a line but just those forming the majority of the deposit and that the great distance reached by the coarse grains is not a phenomenon observed in the nature (view from the laser scanner position).

3.4 Shape and structures of the deposits

During the different experiments, four different deposit shapes have been observed depending of the grainsize (Figure 7). The deposit in the Figure 7a is characteristic for coarse grain. The mass is clearly separated of the tilting plane and there are no grains between the mass and the slope break. The mass is relatively flat with ovale shape and the splash area is quite extended. For a finer grainsize (e.g. F16 or F36), the mass tends to stop at the foot of the slope (Figure 7b) and the splash area is less extended. The part of the mass close to the slope is narrow compared to the front. When the grainsize is finer (e.g. F60), the mass is not separated from the slope (Figure 7c), besides, the back part of the mass remains on the tilting plane. The splash area is less extended than the previous cases but is still detached of the slope break. The last shape (Figure 7c) is observed with the finest grainsize (e.g. F120). In this case, an important part of the mass remains on the slope and the lateral extensions follow the break of slope. The splash area is less extended compared to the other cases and its edges are following the break of the slope. In the Figure 6a and b, we can see that the shapes correspond to the case (d) in the Figure 7 whereas the Figure 6c correspond to the case (c) in the Figure 7.

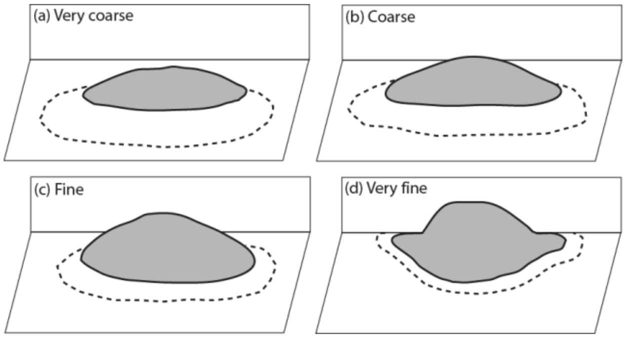

Figure 7. Different shapes of deposits observed during the tests for very coarse grainsize (a), coarse grainsize (b), fine grainsize (c) anf very fine grainsize (d). The grey area represents the main part of the deposit while the area enclosed by the dashed line represents the splash area**.**

Structures perpendicular to the flow direction can be observed on the top of the deposits, especially with the finer grainsize (Figure 10a and b). These structures are interpreted as compressive features and seemed to be formed when the back of the mass that is still in movement while the front is already stopped. These structures are sometimes cut by smaller others that are parallel to the flow direction. They seem to be caused by the deceleration of the back of the mass. These kinds of features have been observed in the Frank Slide deposit by Charrière (2011). In the case of the Frank Slide, the perpendicular (to the propagation direction, Figure 8c) features are interpreted as the expression of the underneath topography. The longitudinal features (Figure 9d) are assumed to be morphological features that were created during the propagation and deposition process (Charrière, 2011).

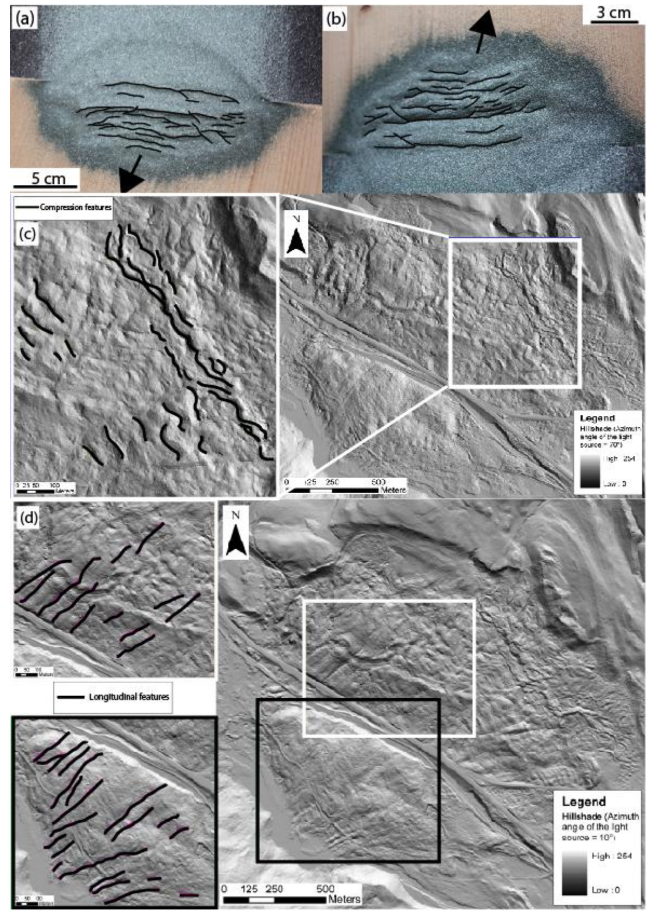

Figure 10. Features observed in the deposits from the front (a) and above (b). Features perpendicular to the flow direction (c) and parallel (d) in the Frank Slide deposit (after Charrière 2011, DEM from Geological Survey of Alberta).

3.5 Fahrböschung

Figure 11 shows the variation of the Fahrböschung as a function of the grainsize and summarized all the results. The experiments with the lower Fahrböschung are those with a slope of 40° (dashed line with white symbols in Figure 11). The Fahrböschung is slightly higher when a substratum is added on the surface of deposition (black line with black symbols in Figure 11). In this case, the Fahrböschung increases when the grainsize decreases. The higher Fahrböschungs are with a 60° angle (dashed line with black symbols in Figure 11). The grey and cross symbols represent the three experiments with mixed grainsizes and different volumes. The smaller volume (grey square surrounded in black in Figure 119) has a smaller Fahrböschung than the greater volumes (grey square and cross). The apparent coefficient of friction is mainly influenced by the slope break, the roughness of the path the sliding mass and by the volume. In addition, as pointed by Perla et al. (1980), the abrupt change in slope angle can have an effect on the loss of kinetic energy.

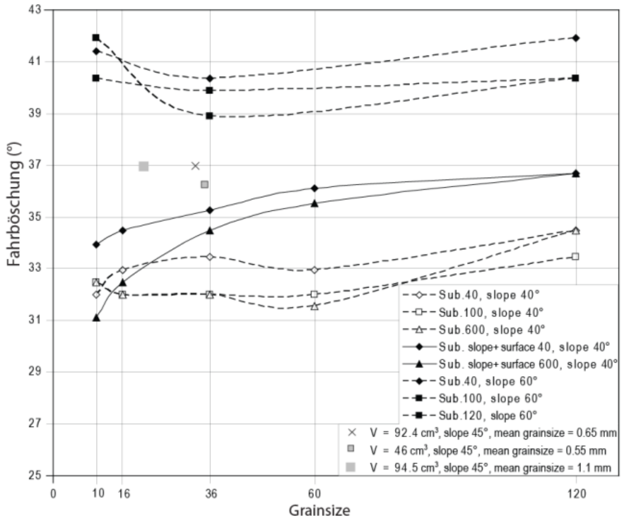

Figure 11. Fahböschung in function of the grainsize for all tests. The dashed line with white symbols corresponds to the experiments with a slope of 40° for all the graisizes and the three substratums on the slope. The full line with black symbols corresponds to the experiments involving a substratum on the slope of 40° but also on the surface of deposition. The dashed line with black symbols corresponds to the experiments with a slope of 60° on the three substratums. The two grey squares and the cross correspond to the experiments involving different volumes with mixed grainsizes (the position on the x-axis corresponds to the mean grainsize).

4 DISCUSSION

As it can be seen in the Figure 11, the Fahrböschung of all the experiments vary between 31.1° and 41.9° (corresponding to an apparent coefficient of friction of 0.6 – 0.9). Some events with same characteristics have been observed by different authors. Table 8 gives the value of three different rock avalanches.

Table 8. Characteristics of the three events that gives values similar to those obtained during the experiments.

Locality of the evens	Fahrbösch-ung (°)	H/L	Volume ($10^6 m^3$)	Authors
Lecco, 1969	41.3	0.88	0.03	Scheideger, 1973
Airolo, 1898	33	0.64	0.5	Hsü, 1975
Schächental, 1887	30	0.58	0.5	Hsü, 1975

The coarser grains tended to be at the top of the deposit when the mass is formed by different grainsizes. In fact, this phenomenon has been observed in the Frank Slide by Cruden and Hungr (1986). They demonstrated that the deposit is inversely graded with fine particles at the bottom (no boulders are found) and the larger boulders dominate the surface of the deposit.
Based on the classification made by Hewitt (2002), the deposits are similar to the one of the Blackhawk in California, the Brazeau Lake in Canada (Cruden, 1982), the Martinez Mountain in California (Bock, 1977) or even to the "Unconfined landslide 9', Coprates Chasma in the Planet Mars (Lucchitta, 1979). Hewitt (2002) classified them as simple (unconstrained) runout. Cruden and Hungr (1986) also observed in the Frank Slide that, on the slide margins that did not climb on the slopes of the opposite valley, the margins are constituted of fine material. The same observation was made when the mass is formed by different grainsizes (Figure 6). Cruden and Hungr (1986) explain this deposition by assuming that the finer particles flowed this position and preceded the coarser material during the motion. Moreover, the shape of the deposit is influence by the size of the grains. In fact, the coarser the grainsize is, the further of the slope break the mass goes. It also influences the splash area that is less extended when the particles are finer.

5 CONCLUSION

This study showed that, even in small scale, a collapsing mass has similarities with real case of rock avalanche. Indeed, the roughness of the substratum and the grainsize influence the runout distance as well as the volume and the angle of the slope. The coarser the grainsize is, the higher is the runout distance and that for all the roughness of the slope and surface of deposition. The coarser grains are on the top of the deposit and the splash area is formed by the finer particles, as it was observed in the Frank Slide,
To improve the comprehension of the rock avalanches, the next major steps of our research are going to be:

- The improvement of the installation, in particular the system for the release of the mass and find a method to analyse the inner part of the deposits in order to understand the deformation stuctures.
- Recording the flowing mass with a high speed camera in order to understand the behaviour of the different grainsize during the flowing and the deposition. It will also allow the particles tracking during the sliding mass and tracking of the front.
- A major step will be to extend the method for the debris flows.
- The analysis using the center of mass has to be investigate to perform an analysis of the conversion of the potential energy in kinetic energy and dissipation.

ACKNOWLEDGEMENTS

The authors are grateful to the reviewer for his constructive comments that improved the manuscript. A special thank to C. Froese , for the Geological Survey of Alberta, who provided the DEM on the Frank Slide.

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