Head Formation in Light Granular Avalanches

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ABSTRACT

A sufficiently developed natural avalanche always has a head at the front end and a tail at the rear end. To experimentally simulate avalanches with such a head-tail structure, avalanche experiments were carried out using table tennis balls, golf balls and styrene foam particles, etc. as a model material for snow. As a result, only in the granular avalanches of light materials, clear heads were formed. From these experiments and theoretical analysis, it was found that the similarity of the formation of this structure relates to the chute length L and the accelerlation of gravity g and the terminal velocity of the granular avalanche on the chute V_e through a dimensionless number V_e^2/Lg. When $V_e^2/Lg << 1$, the head-tail structure is formed.

1. INTRODUCTION

Most of avalanche researchers have never been directly caught up into actual avalanches. If such an experience were not very dangerous, it might be very signifficant for the advance of the avalanche science. To do this safely, using light particles such as table tennis balls (TTB) and styrene foam particles (SFP) instead of snow or sand, we are conducting model experiments of avalanches on small slopes (Kosugi et al. 1995 and Nishimura et al. 1996). In these avalanches, observers can obtain scientific information of the avalanche close at hand without danger. In these experiments, the similarities between natural avalanches and model experiments are essentially significant to estimate any results of the model experiments.

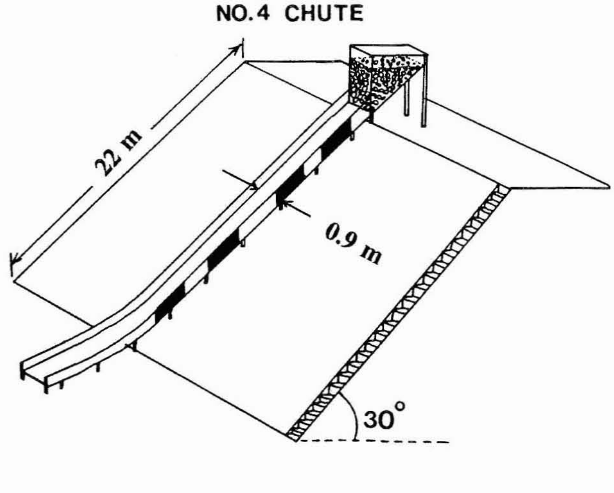
One of the most impressive properties of the shape of large scale natural avalanches is that they have a head-tail structure like a tear drop as is well known in gravity current. Savage and Noguchi (1988), Nohguchi et al. (1990) and Hutter and Nohguchi (1991) examined the behavior of granular avalanches by qualitative analysis of the similarity solutions. As a result, a body of granular material always spreads on a even slope, but a head-tail structure could not be formed using their theoretical frame work. Water tank experiments have also been used to study powder snow avalanches. In water tank experiments, heads similar to gravity currents always appear.

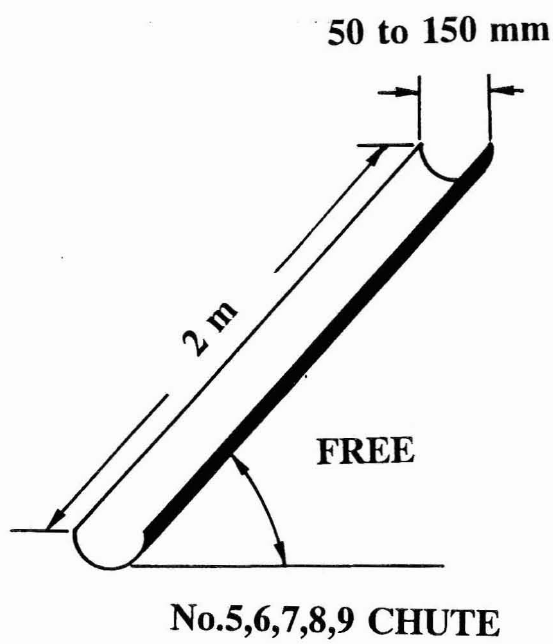
In this paper, we will show the mechanism of the head formation and the similarity of the head-tail structure for model experiments on a reduced scale slope.

2. MODEL EXPERIMENTS

Chutes and particles used in these experiments are summerized in Tables 1 and 2 and Figs 1 and 2 respectively. The long chutes of 10 m order (No.1-4) are for TTB, PB (plastic ball) and GB (golf ball) avalanches and the small chutes of 1m order (No.5-10) are for SFP and PP (plastic particle) avalanches.

In each avalanche experiment, all particles before start are at rest and by opening a gate start to flow down along a chute. The avalanches are recorded by video cameras to obtain their shapes and velocities during flowing down.





Figures 1 Chutes used in these experiments.

Table 1. Summary of chutes

Chute No.	Length m	Width m	Inclination degree	Location
1	20	1.0	30	Shinjo
2	20	0.9	40	Tohkamachi
3	40	0.4	40	Tohkamachi
4	20	0.9	30	Nagaoka
5*	2	0.05	free	-
6*	2	0.075	free	-
7*	2	0.1	free	-
8*	2	0.125	free	-
9*	2	0.15	free	-
10	2	0.05	free	-

*Half pipe chutes.

Table 2. Summary of particles

Particle	Weight g	Diameter mm	Bulk density* kg/m³	Max. Number
TTB 1	2.5	38	64	30000
TTB 2	2.2	44	37	2000
TTB 3	2.0	38	52	2000
PB	7.0	40	155	2000
GB 1	45	43	750	1000
GB 2	25	43	445	2000
SFP 1	0.0033	6	8.2	2700
SFP 2	0.0008	3-4	13.2	15000
SFP 3	0.0002	1.5-2	16.8	18000
SFP 4	0.0026	5	22.3	7500
PP	0.11	5	600	1200

*Bulk densities for TTB, PB and GB are theoretically given by the closest packing.

3. RESULTS

3.1 Head-tail structure

Fig.3 shows typical examples of the side views of TTB avalanches and GB avalanches, etc. at the window 18m down from the starting position. These pictures are successive snapshots taken by a high speed video camera in every 0.25 sec. The TTB avalanches of light particles have a head-tail structure. In the GB avalanches of heavy particles, however, the head-tail structure is not formed yet, but the particles are scattered at the front end as well as at the rear end. These results are similar to those of SFP and PP avalanches on reduced scale in comparison with TTB and GB avalanches.

3.2 Variation of velocity

The variation of the front velocity of a TTB avalanche from start is shown in Fig.4. In the avalanches first, the velocity increases with distance from the start point and then the steady one is almost reached. On the other hand, GB avalanches are still accelerating during these experiments.

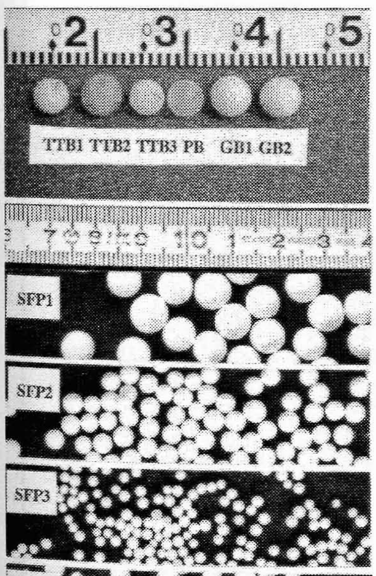


Fig.2 Particles used in these experiments.

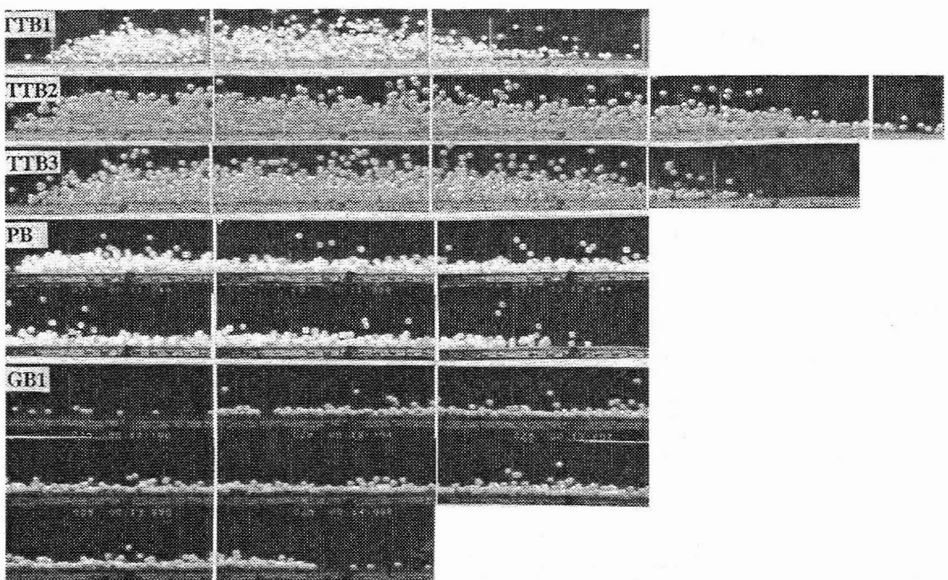


Fig.3 Side views of model avalanches.

3.3 Effect of number

The effect of the number of particles on the front velocities is shown in Fig.5 as for the TTB 1 avalanches. Immediately after start, at 2 m down from start point, the effect of the number of particles is not very large. But as the avalanches flow down the effect becomes larger. The front velocity increases with the increasing number of the particles whose number is more than a hundred. When the number of balls is less than a hundred, each particle moves independently. So the effect of the number is negligible.

Fig.6 shows an example of the relations between the number of particles and velocities of a front end and a rear end under an nearly steady motion. In this example, the front velocity is higher than the rear velocity when the number of the particles is more than a thousand, so the avalanches increasingly elongate under the head-tail structure. When the number is less than a thousand, a particle at the rear end is faster than that at the front end. As a result, the length of the group of the particles is maintained with circulation of the particles between the front end and the rear end.

3.4 Effect of inclination of chute

Fig.7 shows the sideviews of SFP avalanches near the front ends with different inclination angles of the chute No.10. The circulation of the particles at the head depends on the inclination angle.

4. SIMILARITY OF HEAD-TAIL FORMATION

As shown in Fig.5, a bigger group of particles has a faster terminal velocity. Thus the front group always must be the biggest group of particles when the terminal velocity is reached. A smaller group is overtaken by a bigger group. As a result, the concentration of particles occures at the front end, which becomes a head (Fig.8a). On the other hand, if a smaller group is at a rear end, the distance between the smaller group and the main body increases with time. As a result, at a rear end, the group of the particles is increasingly extended and becomes a tail (Fig.8b). Thus, the head-tail structure is formed (Fig.8c).

The appearance of the head-tail structure indicates that the terminal velocity of the group have been reached; in other words, the motion is steady under the balance between the force of gravity and forces resisting. Air drag is one of the mechanisms that defines the terminal velocity. Air drag is dominant for light materials.

Phenomena which accelerate to reach a steady motion are, in general, characterized by the terminal velocity, V_e, the acceleration of gravity, g, and a system size such as a

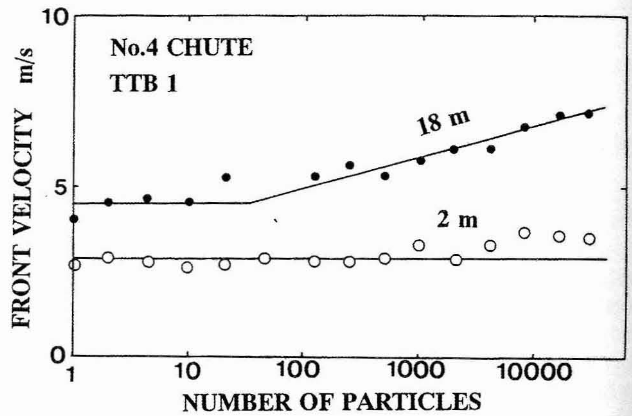


Fig.5 Relation between front velocity and number of particles.

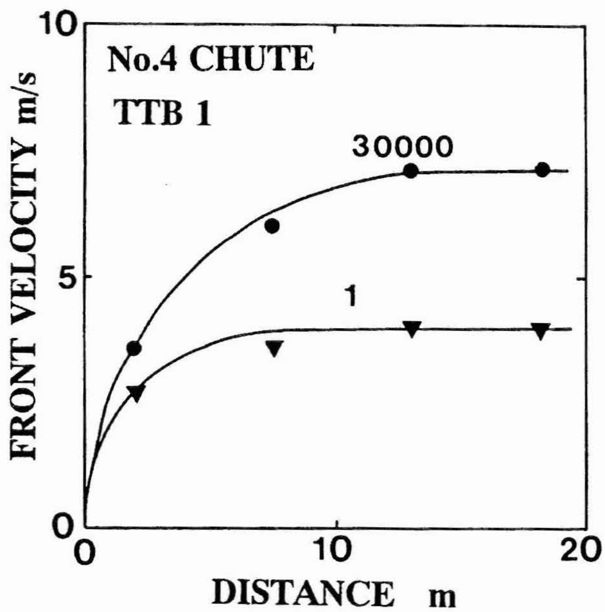


Fig.4 Variation of front velocity of a TTB avalanche with flow distance.

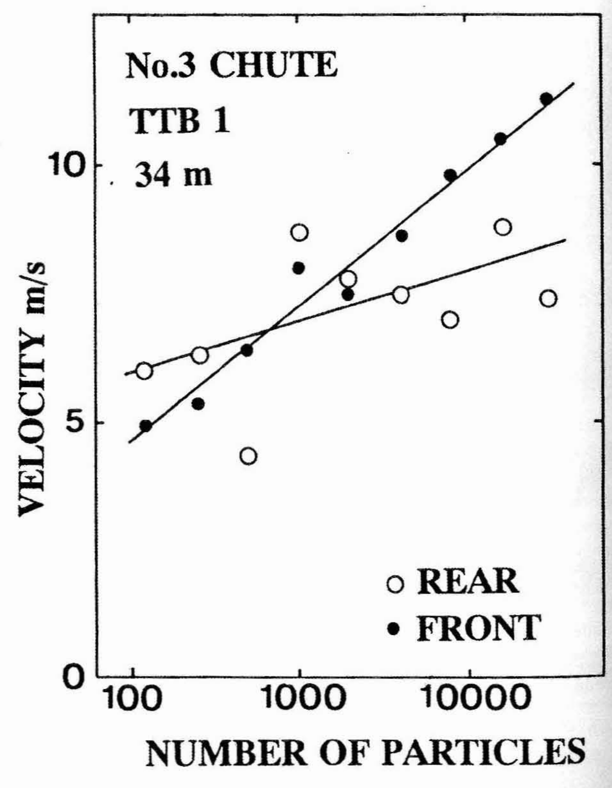


Fig.6 Relation between front and rear velocityies and number of particles.

slope length, L. Using these parameters, We derive a similarity law for a simple model of a granular avalanche.

The equation of motion of a group of granular material is as follows;

$$m\,dv/dt = mg(\sin\theta - \mu\cos\theta) - \alpha v \qquad (1)$$

$$dx/dt = v \qquad (2)$$

where m and θ are the mass and inclination angle of chute respectively, and μ and α are the coefficients of the resisting force.

To make Eqs.(1) and (2) dimensionless, let velocity, v, distance, x, and time, t, be

$$v = Vv,\ x = Lx,\ t = Tt. \qquad (3)$$

where V and T are the scales of velocity and time respectively.

Then Eqs.(1) and (2) are

$$dv/dt = Tg^*/V - (Tg^*/V_e)v = Tg^*/V(1 - (V/V_e)v) \qquad (4)$$

$$dx/dt = (TV/L)v \qquad (5)$$

where

$$mg^*/\alpha = V_e,\ \ g^* = g(\sin\theta = \mu\cos\theta). \qquad (6)$$

If

$$T = V_e/g^* = T_c, \qquad (7)$$

$$L = V_e^2/g^* = L_c, \qquad (8)$$

$$V = V_e, \qquad (9)$$

then Eqs.(4) and (5) are

$$dv/dt = 1 - v \qquad (10)$$

$$dx/dt = v. \qquad (11)$$

This means that both accelerating motion and steady motion appear under the scales represented by Eqs.(7)-(9).

If

$$V = V_e \text{ and } L >> L_c, \text{ that is, } T >> T_c, \qquad (12)$$

then Eq.(4) is

$$v = 1. \qquad (13)$$

This means that the steady motion is dominant under the scaling condition represented by Eq.(12), which also can be described by dimensionless number as:

$$V_e^2/Lg^* << 1. \qquad (14)$$

Therefore, Eq.(14) or Eq.(12) governs the formation of the head-tail structure. V_e^2/Lg^* is a kind of Froude number (we call this system size Froude number) that V and L are the terminal velocity and slope length, respectively.

If $V << V_e$, (15)

then

$$dv/dt = 1. \qquad (16)$$

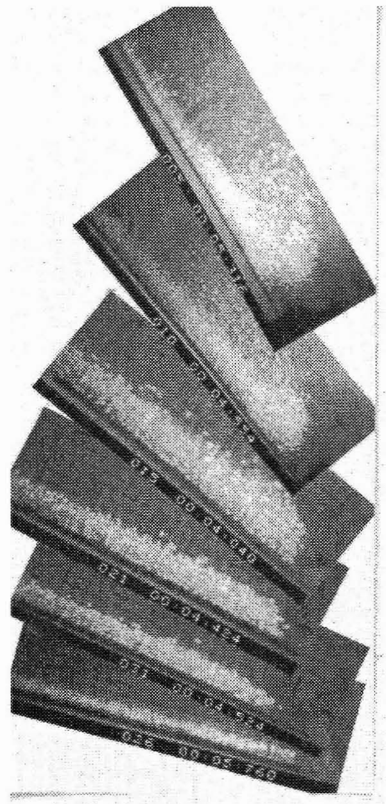


Fig.7 Side views of SFP 2 avalanches.

In this case, only acceleration is dominant, therefore, the head-tail structure cannot be formed.

In table 3, typical cases in natural avalanches and granular avalanches are summarized for the same system size Froude number, 0.1. TTB avalanches on 25 to 100 m slope and SFP avalanches on 1 to 4m are similar with natural powder snow avalanches on a few kiro meters slope, and the head-tail structure is formed. However, the system

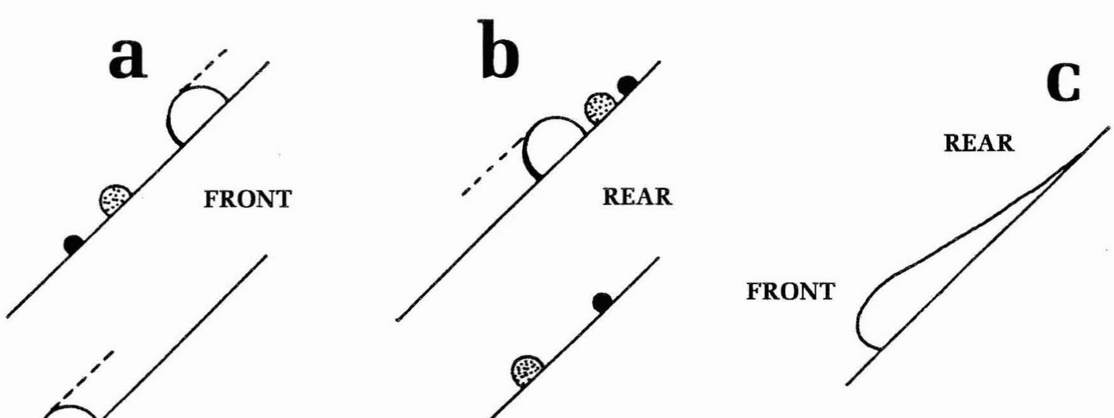


Fig.8 Schematic diagram of head-tail structure formation.

Table 3. Comparison of various kinds of avalanches

Avalanches	Speed V_e m/s	$T_c=V_e/g$ s	$L_c=V_e^2/g$ m	Slope length m	$L\ V_e^2/Lg$
SFP	1	0.1	0.1	1	0.1
SFP	2	0.2	0.4	4	0.1
TTB	5	0.5	2.5	25	0.1
TTB	10	1.0	10.0	100	0.1
Snow	20	2.0	40.0	400	0.1
Snow	50	5.0	250.0	2500	0.1
GB	50	5.0	250.0	2500	0.1

size Froude numbers for GB avalanches on 20 m long slopes and PP avalanches on 2 m long slopes are about 1 and 10 respectively. Therefore, the head-tail structure can not be formed yet on the slopes used in these experiments.

5. CONCLUSIONS

From a theoretical analysis, we found that the similarity of the head-tail structure relates to the chute length L, the acceleration of gravity g and the terminal velocity of the granular avalanche on the chute V_e through a dimensionless number V_e^2/Lg (a system size Froude number). When $V_e^2/Lg << 1$, the head-tail structure is formed. This condition corresponds to avalanche motion that is almost steady; therefore, a light granular material, or a long chute is favorable for the formation of the head-tail structure because a light granular avalanche has a low terminal velocity. This means that a light granular material such as styrene foam particles is good for model experiments of avalanches on a reduced scale.

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