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Effect of grain diameter and packing condition on the avalanching depth on a slope composed of dry granular materials

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Abstract

To examine the depth of avalanching taking place on a slope at a critical angle of repose, tilting tests were performed in the laboratory using slopes made of granular materials such as gravels and glass beads. Results show that the avalanche depth, Z, is determined by the diameter of the slope materials, d_m, and the volume concentration of the slope materials, C, such that $Z = 4.8\ d_m/C$.

Key words: avalanche depth, granular slope, tilting test, angle of repose

1. Introduction

Our previous laboratory experiment (Matsukura and Onda, 1999) reported that the avalanche depth in slopes composed of granular assemblies is about eight times the diameter of the slope material. This experiment was carried out using 'specific slopes' made by piling up cylindrical aluminium rods, *i.e.*, two-dimensional material. The present study accordingly examines the avalanche depth for slopes consisting of three-dimensional granular materials such as gravel, sand (landform materials) and glass beads.

In natural conditions, landform materials are three-dimensional materials which have a variety of packing states such as 'dense' and 'loose' packing, corresponding respectively to high and low density of the materials. Slope materials may change in density with time; for example, the density may decrease due to weathering or increase due to the filling of pores by fine materials. It is therefore important to examine the effect of density on the avalanche depth on slopes consisting of three dimensional materials.

2. Experimental materials, apparatus and procedure

2.1. Slope material

Several slope materials are used in the present study, namely sand, glass beads and three kinds of gravel: (1) beach shingle (sandstone), (2) river gravel (crystalline schist), (3) crashed stone (arkose-sandstone). The sand is Toyoura-Standard-Sand, which consists of well-sorted quartz sand grains. The two sizes of glass beads have a uniform diameter of about 2.2 mm and 5.3 mm. Beach shingle was collected from Kashima, Ibaraki, and river gravel from Naruto, Tokushima. Crashed stone is arkose-sandstone, and is a construction material available commercially from Tsukada-Tokan K. K. Co., Tsukuba. The glass beads are spherical (Krumbein's roundness = 1.0), but particles of the other materials have various shapes. The roundness of these materials is 0.8 for sand and beach shingle, and is 0.5 for river gravel and 0.2 for crashed stone (Matsukura *et al.*, 1989).

All 26 samples used as slope materials, denoted A through Z as shown in Table 1, were prepared as pure samples of these materials or mixtures of them. For example, Sample I is a mixture of the two kinds of glass beads, in the ratio 1:1 by weight. Samples N and V are unimodal materials of crashed stone and sand, respectively, and Samples O through U are gravel-sand mixtures, *e.g.*, Sample O is 70 % gravel and 30 % sand by weight, and Sample P is 60 % gravel and 40 % sand.

Fifty particles were selected randomly from each of the 26 samples. Three characteristic lengths of these particles were measured: the long diameter, d_l, the intermediate diameter, d_m, and the short diameter, d_s. In the case of sand, only d_l and d_m values for 18 particles were measured, using a photograph through the microscope. These values of the mixing material were calculated by considering a mixture ratio (Table 1).

The same two materials were used in the following seven pairs of cases: A and B, C and D, E and F, J and K, L and M, W and X, and Y and Z. The degree of compaction was different, however; the first named is loose packed and the latter is densely packed. These packing states are described in detail in the next section.

2.2. Apparatus and experimental procedure

Since (1) the slope materials have the size of gravel, and (2) the ratio of the slope length to the diameter of slope material (l/d) should exceed 60 or 70 for avalanching to occur at the angle of repose (Onda and Matsukura, 1989), a large-sized tilting box was used. The apparatus comprises a triangular-prism-like box, which has a length of 100 cm, width 80 cm, and height

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Table 1 Basic data on slope material and slope length.

Case	Slope material								Slope length	
	Test specimen (mean diameter, mm)	Mixing ratio by weight	Long diameter, d_l (mm)	Intermediate diameter, d_m (mm)	Short diameter, d_s (mm)	True density (g/cm^3)	Bulk density (g/cm^3)	Fractional volume concentration, C	Slope length, l (cm)	l/d-value
A	Beach shingle (7.0)	Unimodal	14.4	9.50	5.90	2.56	1.59	0.62	117	123
B	*ditto*	Unimodal	14.4	9.50	5.90	2.56	1.68	0.65	115	121
C	River gravel (7.5)	Unimodal	21.2	10.1	5.50	2.85	1.72	0.60	113	112
D	*ditto*	Unimodal	21.2	10.1	5.50	2.85	1.80	0.63	111	110
E	River gravel (15.0)	Unimodal	34.8	17.1	10.6	2.85	1.67	0.59	120	70
F	*ditto*	Unimodal	34.8	17.1	10.6	2.85	1.80	0.63	116	68
G	Glass beads (2.2)	Unimodal	2.20	2.20	2.20	2.44	1.50	0.61	110	500
H	Glass beads (5.3)	Unimodal	5.28	5.28	5.28	2.44	1.51	0.62	115	218
I	Glass beads (2.2) and (5.3)	1:1	3.74	3.74	3.74	2.44	1.62	0.66	110	294
J	Crashed stone (3.5)	Unimodal	6.90	4.50	2.40	2.60	1.29	0.50	116	258
K	*ditto*	Unimodal	6.90	4.50	2.40	2.60	1.41	0.54	112	249
L	Crashed stone (10.6)	Unimodal	17.2	12.1	7.10	2.60	1.38	0.53	121	100
M	*ditto*	Unimodal	17.2	12.1	7.10	2.60	1.53	0.59	116	96
N	Crashed stone (9.7)	Unimodal	17.2	12.1	7.10	2.70	1.48	0.55	116	96
O	Crashed stone (9.7) and sand (0.24)	7:3	12.1	8.54	no data	2.69	2.05	0.76	116	136
P	*ditto*	6:4	10.4	7.35	*ditto*	2.68	2.05	0.77	116	158
Q	*ditto*	5:5	8.75	6.17	*ditto*	2.62	1.87	0.72	116	188
R	*ditto*	4:6	7.07	4.98	*ditto*	2.63	1.81	0.69	116	233
S	*ditto*	3:7	5.38	3.79	*ditto*	2.60	1.69	0.65	116	305
T	*ditto*	2:8	3.69	2.61	*ditto*	2.58	1.61	0.62	116	446
U	*ditto*	1:9	2.00	1.42	*ditto*	2.59	1.52	0.59	116	815
V	Sand (0.24)	Unimodal	0.31	0.23	*ditto*	2.62	1.41	0.54	117	5028
W	Crashed stone (9.7) and (13.7)	5:5	20.6	14.3	9.26	2.70	1.40	0.52	116	81
X	*ditto*	5:5	20.6	14.3	9.26	2.70	1.49	0.55	114	80
Y	Crashed stone (6.8) and (9.7)	5:5	16.7	10.9	6.64	2.70	1.43	0.53	117	107
Z	*ditto*	5:5	16.7	10.9	6.64	2.70	1.63	0.61	114	104

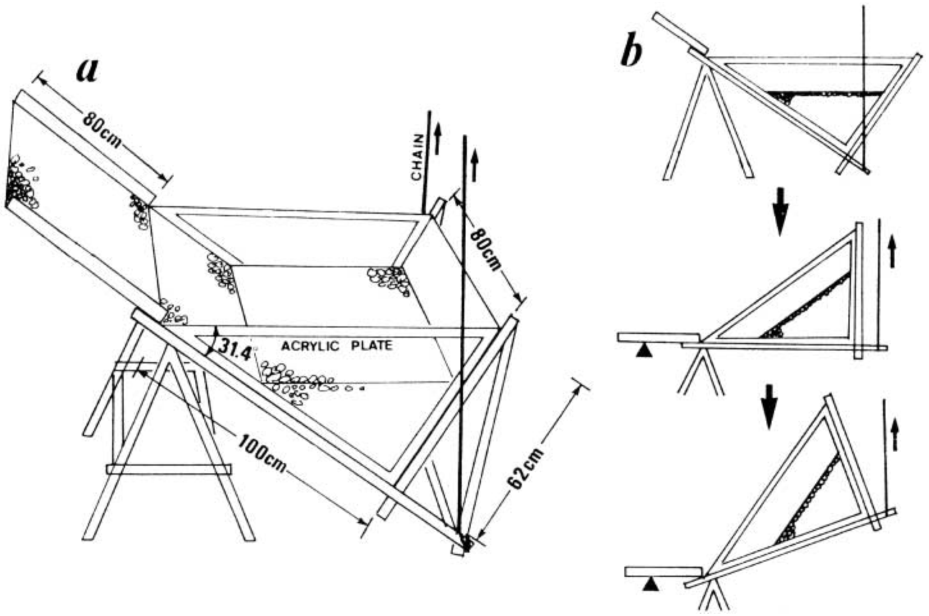

Fig. 1 Tilting box equipment used in the present study.

62 cm (Fig. 1a: Onda *et al.*, 1988). The width was varied from 40-26 cm by inserting a plate in the centre of the box. The frame and backboard were made of wood and plywood. The side of the box, being triangular, is made of a transparent acrylic plastic plate to allow observation of the behavior of the avalanche from the side. The base and front of the box, allowing runout of avalanche material, are made of the same material as the slope material, glued to a plywood surface to generate roughness.

The experimental procedure is as follows:

(1) Sufficient amounts of slope materials are slowly pored into the box. A slope was consequently made of loosely packed materials. The densely packed cases (samples B, D, F, K, M, X and Z), were induced using a vibrator. The total weight and total volume of the sample were measured and the bulk density of the sample was then calculated as weight/volume.

(2) The upper surface of the materials in the box was set up to be horizontal, and the initial profile of the slope surface was measured.

(3) As shown in Fig. 1b, the back side of the box was set to tilt by pulling the chain at a (slow) angular speed of 0.1-0.2 deg/s, gradually increasing the slope angle.

(4) With increasing slope angle, several particles sporadically roll down, and then the mass of slope material slips and flows down the slope.

(5) When the avalanche extends to the whole slope, the chain pulling is stopped.

(6) The angle at the time when the avalanche occurs is obtained accurately from a digital clinometer set on the box. This angle is defined as the 'critical angle' (Carrigy, 1970) or 'angle of initial yield' (Allen, 1969) and is denoted α_c below.

(7) The angle of the slope is measured with a clinometer after each avalanche.

(8) The slope profile after an avalanche was measured on four lines midway between the side walls.

(9) Comparison of profiles before and after the tilting experiment provides the thickness of the avalanche, as explained in detail below.

In procedure (1), we calculated the degree of packing. A more appropriate measure of the volumetric density of packing is the fractional volume concentration, C, which is expressed as (*e.g.*, Allen, 1985, p.27):

$$C = \frac{\text{total volume of grains}}{\text{overall volume of packing}} \tag{1}$$

The values of C were calculated from the bulk density (including voids) and the true density (excluding voids).

The motion of slope materials was observed through the transparent side-walls and was recorded by a 8-mm video camera. Real-time observation and subsequent video images revealed that avalanching materials are accumulated at the lower part of the slope, so that this part of the slope does not show the avalanche plane. The thickness of the avalanche was therefore measured at three points in the zone between the middle and upper part of the slope, specifically at 20, 30 and 40 cm distance from the upper end of the slope. A total of 12 data on avalanche thickness were obtained from the four profiles along the measuring lines in a single test, and the average value is calculated.

Testing with the same conditions was repeated three or four times, and average thicknesses of the avalanche, p, and average angles of repose, α_c, were calculated. The perpendicular depth of the avalanche, Z, was calculated as $p/\cos\alpha_c$.

3. Results and discussion

Table 2 summarizes the results. We examine first the relation between the depth of avalanching, Z, and the mean diameter of slope material, d_m, as shown in Fig. 2. This relation is expressed by the following equation:

$$Z = 7.9\, d_m \tag{2}$$

This equation roughly coincides with the equation ($Z = 7.8\, d_m$; r = 0.99) derived for tests using aluminium rods performed by Matsukura and Onda (1999) and summarized in Table 3, although the data in the present study have a smaller correlation coefficient (0.779) than the aluminium rod data. A further experiment using aluminium rods has been carried out by Matsukura and Terada (2003), and these data are also shown in Table 3. Data from the present study and both aluminium-rod tests are plotted in Fig. 3. This shows the same relation as Eq. (2) with r = 0.843.

Tables 1 and 2 show that the depth of avalanche is different in loose and dense packed states. As well as Matsukura and Onda's (1999) experimental conclusions, Onda (1990) suggests on the basis of mathematical modeling of two-dimensional assemblies that the avalanche depth should be eight times the diameter of the slope material. This ratio in fact differs for different packing states, being smaller for dense packing states

Table 2 Results of tilting tests: angle of repose and avalanching data.

Case	Angle of repose, α_c (degrees)	Avalanche		d_m/C
		Thickness, p (mm)	Depth, Z (mm)	
A	36.1	48.5	60	15.3
B	37.6	52.3	66	14.5
C	40.5	42.6	56	16.7
D	41.2	34.6	46	16.0
E	42.3	71.0	96	29.2
F	43.8	65.7	91	27.0
G	24.8	19.1	21	3.59
H	26.9	58.9	66	8.53
I	24.1	28.3	31	5.65
J	40.8	49.2	65	9.06
K	40.8	27.3	36	8.30
L	43.2	94.8	130	22.8
M	44.2	81.7	114	20.5
N	45.3	86.5	123	22.0
O	41.5	46.4	62	11.2
P	41.7	25.4	34	9.61
Q	38.0	16.5	21	8.62
R	37.0	14.4	18	7.23
S	35.4	19.6	24	5.84
T	35.1	13.1	16	4.18
U	34.9	17.2	21	2.42
V	34.9	29.5	36	0.43
W	46.5	73.2	106	27.5
X	50.4	98.4	155	25.8
Y	45.7	83.4	120	20.6
Z	48.3	92.8	140	18.0

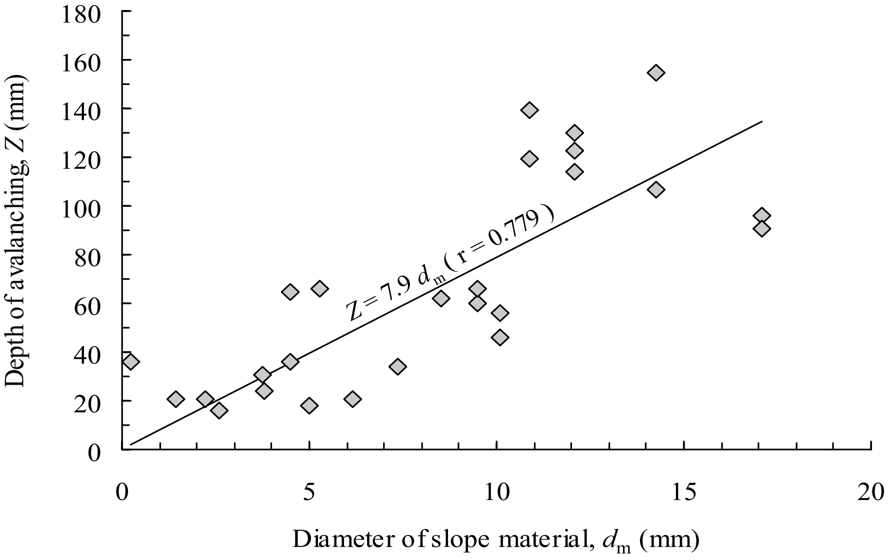

Fig. 2 Relation between avalanche depth, Z, and diameter of slope materials, d_m.

Table 3 Previous data using aluminium rods (Matsukura and Onda, 1999, and Matsukura and Terada, 2003).

Slope material								Slope length			Avalanche			
Test specimen (mean diameter, mm)	Mixing ratio by weight	Long diameter, d_l (mm)	Intermediate diameter, d_m (mm)	Short diameter, d_s (mm)	True density (gf/cm^3)	Bulk density (gf/cm^3)	Fractional volume concentration, C	Slope length, l (cm)	l/d -value	Angle of repose, α_c (degrees)	Thickness, p (mm)	Depth, Z (mm)	d_m/C	Source
Aluminium rod (1.6) and (3.0)	4:1	50	1.88	1.88	2.69	2.24	0.83	20	106	29.3	14.3	16.4	2.26	Matsukura and Onda (1999)
	3:2	50	2.16	2.16	2.69	2.22	0.83	20	93	28.6	15.5	17.6	2.62	
	2:3	50	2.44	2.44	2.69	2.29	0.85	20	82	29.5	16.6	19.1	2.87	
	1:4	50	2.72	2.72	2.69	2.33	0.87	20	74	29.7	17.9	20.6	3.14	
Aluminium rod (3.0) and (5.0)	9:1	50	3.2	3.2	2.69	2.3	0.86	28.5	89	27.5	25.5	28.8	3.74	
	3:2	50	3.8	3.8	2.69	2.22	0.82	30	79	28.1	28	31.7	4.61	
	2:3	50	4.2	4.2	2.69	2.29	0.85	34	81	28.5	28.1	32	4.94	
	1:4	50	4.6	4.6	2.69	2.32	0.86	38	83	27	31.5	35.4	5.32	
Aluminium rod (5.0) and (9.0)	20:1	50	5.19	5.19	2.69	2.32	0.86	38	73	30.5	34.5	40	6.01	
	4:1	50	5.8	5.8	2.69	2.32	0.86	39	67	29.2	37	42.4	6.72	
	3:2	50	6.6	6.6	2.69	2.29	0.85	40	61	26.2	47.2	52.6	7.74	
	5:4	50	6.78	6.78	2.69	2.35	0.87	41	60	26.1	46.6	51.9	7.76	
Aluminium rod (1.6) and (3.0)	4:1	50	1.88	1.88	2.69	2.22	0.83	20	106	28.68	1.71	19.4	2.28	Matsukura and Terada (2003)
	3:2	50	2.16	2.16	2.69	2.22	0.83	20	93	28.6	1.49	17	2.62	
	2:3	50	2.44	2.44	2.69	2.29	0.85	20	82	29.62	1.69	19.4	2.87	
	1:4	50	2.72	2.72	2.69	2.33	0.87	20	74	29.84	1.91	22	3.14	

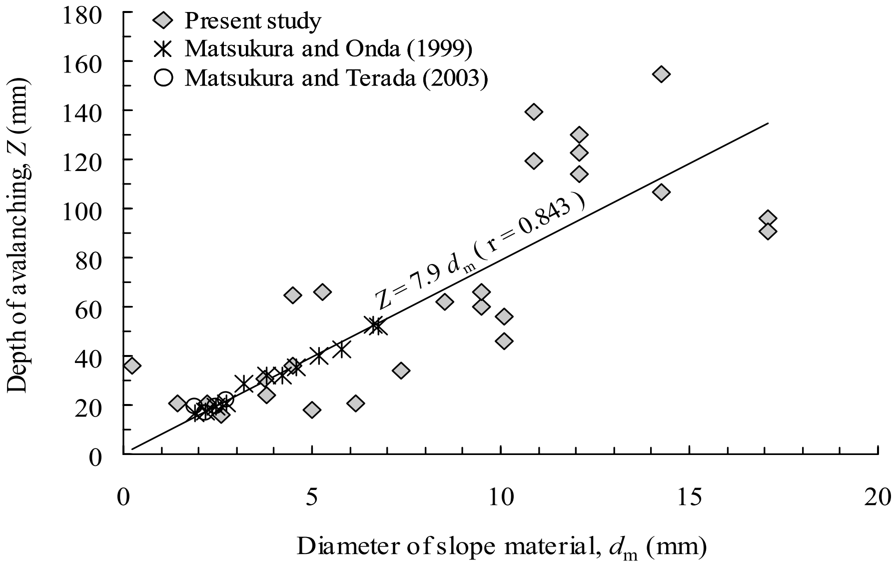

Fig. 3 Relation between avalanche depth, Z, and diameter of slope materials, d_m, including the data for aluminium rods.

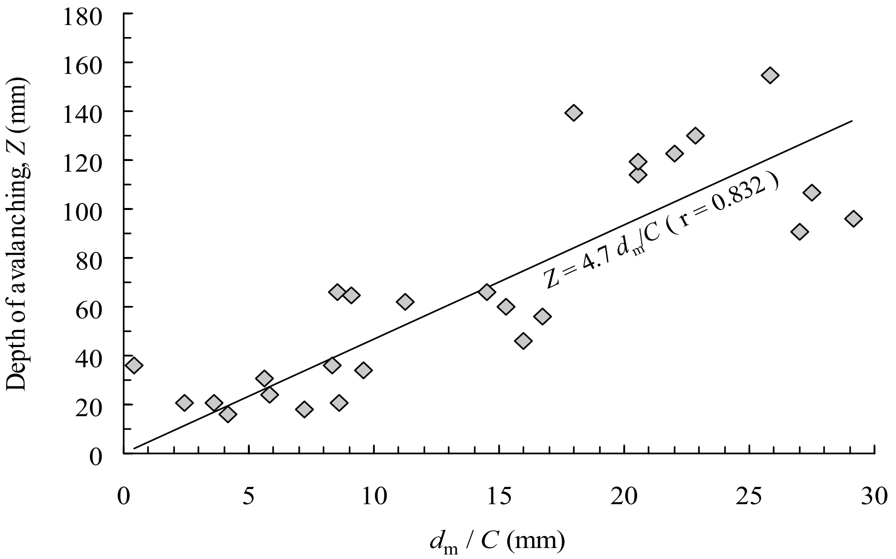

Fig. 4 Relation between avalanche depth, Z, the diameter of slope materials, d_m and the volumetric density of packing, C.

(large C value) and larger for loose packing states (for small C value). This implies that the packing state affects the avalanche depth: the Z-value increases with decreasing C-values, *i.e.*, $Z \propto d_m/C$. We therefore examine the relation between Z and d_m/C.

Figure 4 shows a plot of both data indicating the following linear relation:

$$Z = 4.7\ d_m\ /C \qquad (3)$$

with r-value of 0.832. This value is higher than that of Eq. (2), for which r = 0.779. This suggests that the avalanche depth is controlled not only by the grain size but also by the concentration of slope material, *i.e.*, the packing state. All the data, including the tests using aluminium rods, are plotted in Fig. 5. The relation is:

$$Z = 4.8\ d_m\ /C \qquad (4)$$

The constant of proportionality becomes 4.8 rather than

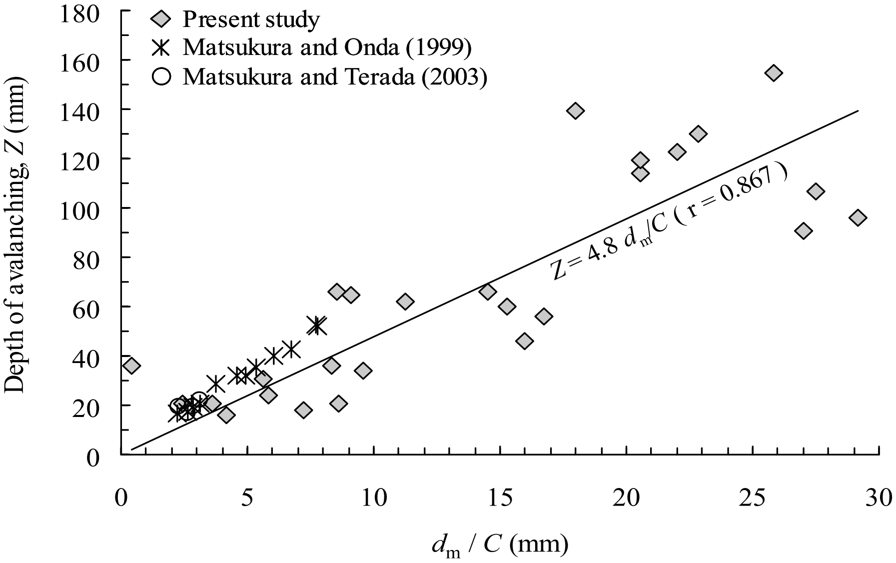

Fig. 5 Relation between avalanche depth, Z, the diameter of slope materials, d_m and the volumetric density of packing, C, including the data for aluminium rods.

4.7 when the aluminium rod data are included, and the r-value becomes higher at 0.867 than in the data from the present study alone.

We conclude that the avalanche depth on slopes made of granular materials is determined by the diameter of the slope materials and by their packing state.

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