International Journal of GEOMATE, July 2023, Vol. 25, Issue 107, pp.1-8
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.107.g12220
Geotechnique, Construction Materials and Environment

EFFECT OF ROCK MASS DIAMETER ON RUNOUT DISTANCE AND VELOCITY ATTENUATION OF DRY GRANULAR AVALANCHE

* Naoto Naito[1], Tatsuya Matsuda[1], Kinya Miura[1], Takumu Omura[1] and Arif Daniel Bin Azmi[1]

[1]Department of Architecture and Civil Engineering, Toyohashi University of Technology, Japan

*Corresponding Author, Received: 15 June 2022; Revised: 11 Dec. 2022; Accepted: 29 March 2023

ABSTRACT: In order to rationalise the existing methods for evaluating the runout distance of rock-slope failure debris, it is necessary to clarify the relationship between the runout distance of granular materials and the materials' flow behavior. In this study, a series of model tests were conducted to analyse the effect of several parameters, including slope angle, flow height, and granular diameter, on the runout distance and flow velocity of particles in dry granular avalanches. Our test results indicate a dependency between runout distance and the characteristics of the granular materials involved. Specifically, we show that when granular materials are present at the toe of a slope, subsequent materials of larger diameter can act to push these preceding materials further out, thereby increasing their effective runout distance. In contrast, we show that if the subsequent granular materials manage to overtake the granular materials already present, and if the velocity of granular materials goes to zero around the toe of the slope, the runout distance of the largest granular diameter may not be maximal. To investigate dry granular avalanche runout distance in cases of secondary slope failure, we conducted an additional series of model tests in which rock masses generated by primary slope failure were deposited at the toe of the slope. These test results indicated that, regardless of the particle size, maximum runout distances in cases of secondary slope failure and primary slope failure avalanches are identical.

Keywords: Rock slope failure, Dry granular material, Granular avalanche, Runout distance, Model test

1. INTRODUCTION

In order to evaluate existing methods for evaluating the runout distance of rock-slope failure debris [1], it proves useful to first clarify the relationship between the runout distance and the flow behavior of granular materials. Recently, the discrete element method (DEM) [2] has seen use in Japan as one of the most promising methods in numerical analysis for predicting the runout distance of debris from rock-slope failure [3]. The proven success of DEMs have prompted their widespread usage in practice; for example, when evaluating critical safety structures including nuclear power plants [4]. This study aims to clarify the slope flow behavior of rock masses and obtain data empirically validating the results of DEM simulations.

Many researchers so far have focused on granular diameter as one of the primary factors affecting the runout distance of rock debris. A series of experiments on the effect of varying grain diameter and collapse volume on runout distance was conducted. It was concluded that rock debris with larger grain diameters attain longer runout distances [5]. Model experiments were conducted with five different granular diameters and three different collapse masses [6] and obtained the similar results to Tochigi [5] in terms of mass centre. Furthermore, series of model tests was conducted that focused on the effect of the mixture of fine or coarse grains in rock debris on runout distance [7]. This study revealed that the observed runout distance reaches a maximal value when the volumetric ratio of coarse to fine grains exceeds 50%. Other studies have investigated the influence of particle size distribution on the deposition distance of granular flows [8, 9]. Numerical analysis was conducted using the DEM to study the variation of the runout distance and energy attenuation mechanism with the granular diameter, particle shape, and slope undulation [10]. A numerical analysis using the DEM was performed to clarify the effects of the grain shape and size on the runout distance; their results suggested a relationship between the segregation of particles with differing characteristics and their collective runout distance [11]. Model experiments and DEM simulations with varying granular diameter and slope angle were conducted; however, because of the short length of the horizontal plane of the model slope, the runout distance was not examined in this study [12]. However, these previous studies do not clarify the effect of a varying slope angle on the runout distance of the rock debris.

Experiments were conducted by varying the slope angle, collapse mass, and particle size [13]; however, only two particle sizes were used. Thus, further investigations need to be conducted to determine the effect of particle size on the runout distance. The maximum slope angle in that experiment was 45°, and thus, the runout distance of granular flow under steep

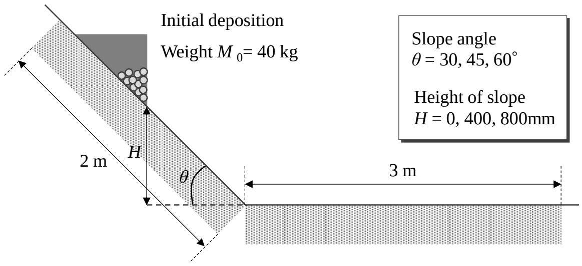


Fig. 1 Outline of slope and initial deposition

slope conditions (e.g., a 60° slope angle) was not known. Some experiments were conducted under steeper slope conditions [14] but not with varied particle sizes.

In the investigations on granular flow, current studies focusing on the flow behaviour of rock debris primarily discuss material flow on the slopes [15, 16]. In contrast, studies on flow modes around the toe of a slope are limited. A complex flow behaviour can occur at the toe of the slope (i.e., at points of abrupt change in the slope angle); this can affect the runout distance. Therefore, the temporal variation of the velocity distribution and associated phenomena must be elucidated so as to enable the accurate prediction of the runout distance of granular flows.

Extant studies have not clarified the effect of a wide range of slope angles and granular diameters on the runout distance of rock debris. However, there is no guarantee that a similar trend would be obtained at other slope angles even if the effect of the granular diameter on runout distance at a given slope angle is obtained. The effect of a wide range of slope angles and granular diameters on the runout distance of rock debris should be clarified to predict the reach of a group of rocks in the event of a slope failure with high accuracy.

In this study, we conducted a series of model tests on rock-slope failure in which we comparatively examined the effects of the slope angle, flow height, and granular diameter on the runout distance. A high-speed camera is used to capture images of a wide area from the slope to the horizontal plane; the flow velocity distribution of the rock debris is measured using particle image velocimetry. This enables the detailed observation of the granular flow behaviour not only on the slope but also at the toe of the slope. The observation of the granular flow behaviour of the toe of the slope is important for analysing the effect of the granular diameter on the runout distance.

2. RESEARCH SIGNIFICANCE

This study focused on the effect of granular diameter on the runout distance of rock debris under a wide range of slope angle and flow height conditions. Therefore, this study is significant because it provides further insight into the effect of the granular diameter when compared with that in earlier studies. In addition, the viewpoint of time variation of the velocity distribution has helped to deepen understanding of the relationship between granular diameter and runout distance. This study has provided fundamental knowledge that contributes to the high accuracy of the prediction of the runout distance of the rock masses.

Table 1 Conditions of model tests

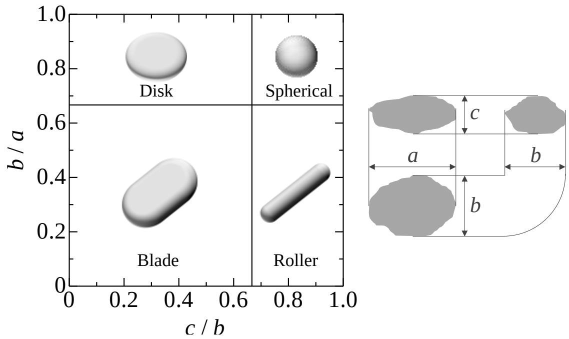
Case No.	Type of trigger gate	θ (°)	H (mm)	M_0 (kg)	Granular diameter
1	Shutter	30	0	40	Small
2					Medium
3					Large
4			400		Small
5					Medium
6					Large
7			800		Small
8					Medium
9					Large
10		45	0		Small
11					Medium
12					Large
13			400		Small
14					Medium
15					Large
16			800		Small
17					Medium
18					Large
19		60	0		Small
20					Medium
21					Large
22			400		Small
23					Medium
24					Large
25			800		Small
26					Medium
27					Large
28	Hinge	45	800	80	Small
29					Medium
30					Large
31				40×2	Small
32					Medium
33					Large

3. CONDITIONS OF MODEL ROCK-SLOPE FAILURE TESTS

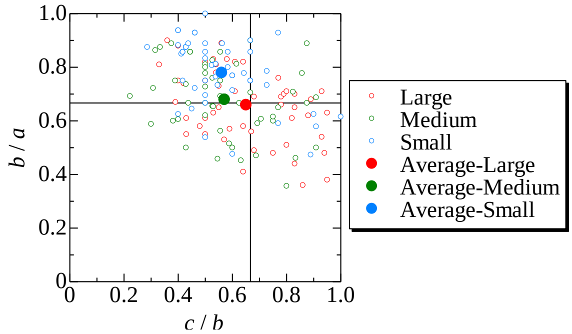
3.1 Outline of Model Tests

Model tests have been conducted using the apparatus shown in Fig. 1, which consists of a slope with a horizontal surface length of 3 m, a face length of 2 m, a connecting hinge used for varying the slope angle, and a trigger gate installed in a 0.4 m wide earthen tank. A shutter-type gate has been used for


Fig. 2 Image of granular materials



(a) Conceptual diagram

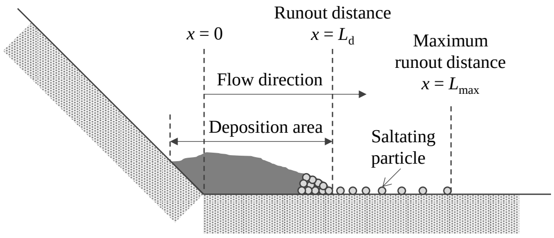


(b) Measurement Results

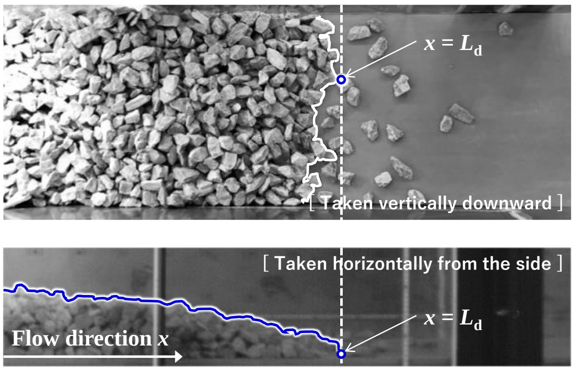
Fig. 3 Shape classification of granular materials

trials using M_0 = 40 kg of rock debris, while a hinge-type gate has been used for the trials using 80 kg of debris. Crushed rocks with grain sizes respectively ranging from 4.75 to 9.50 mm (Small), 9.50 to 19.0 mm (Medium), and 19.0 to 37.5 mm (Large) were used as granular material. The granular shape and other characteristics of the material are further described below.

In the model tests, once granular materials were deposited in a storage container on the experimental slope, the trigger gate was opened, resulting in a granular avalanche. In the case of the shutter-type gate, the shutter was pulled vertically upward velocity of about 1.6 m/s. For the hinge-type gate, the hinge placed above the initial deposition of the granular materials acts as a centre of rotation, causing an instant release of sedimentary soil pressure resulting in the granular avalanche. During the model tests, the slope flow behaviors were photographed at 500 fps from a direction orthogonal to the flow of debris. After the experiment, photographs were taken both orthogonally to the flow direction and from the top of



(a) Conceptual diagram



(b)Photos

Fig. 4 Definition of runout distance

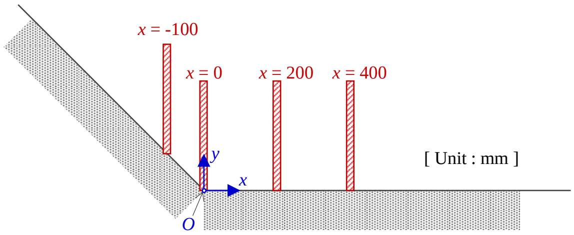


Fig. 5 Time-history velocity measurement area

the soil tank to confirm the runout distance of the granular avalanche and the final deposition shapes.

3.2 Model Test Case

In our model tests, a total of 27 cases of rock-slope failure tests have been conducted using shutter-type open devices with a combination of parameters of granular diameter (small, medium, and large granular materials), slope angle θ (30, 45, 60°), and slope height H (0, 400, 800 mm). Model tests have also been conducted testing the effects of a primary failure followed by a secondary slope failure, and of an instantaneous total collapse in volume. Table 1 outlines the conditions used in these model tests.

3.3 Granular Diameter and Shape Classification

Fig. 2 gives visuals of small, medium, and large granular material, with the mean mass of each particle diameter being 0.36 g, 4.03 g, and 19.85 g respectively. Fig. 3 shows the shape classification [17] obtained from 50 randomly selected major axis diameter a, medium axis diameter b, and minor axis

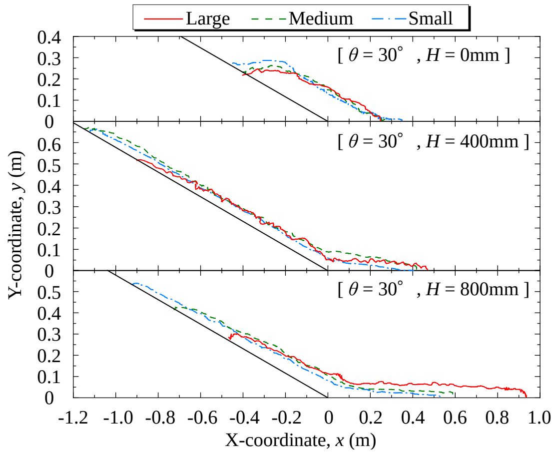


Fig. 6 Final deposition shapes: θ = 30° (Cases 1–9)

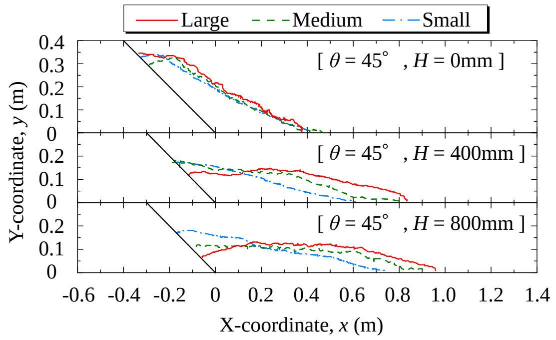


Fig. 7 Final deposition shapes: θ = 45° (Cases 10–18)

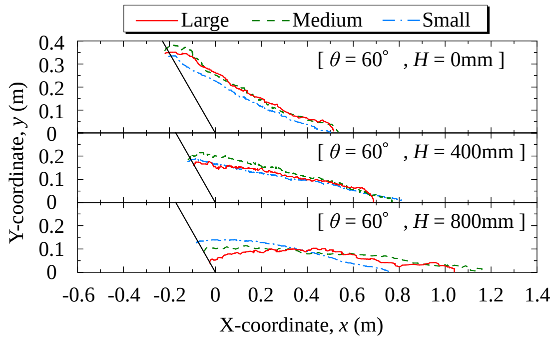


Fig. 8 Final deposition shapes: θ = 60° (Cases 19–27)

diameter c from each particle, and the filled plots show their mean values. All of the granular diameters are generally massive in shape.

3.4 Data Organization Methods

3.4.1 Runout distance

In this study, the final deposition of the granular avalanche has been divided into a depositional area, where rock particles are stacked in two or more levels, and an area containing saltating particles, as shown in Fig. 4 [18]. The runout distance L_d is defined to be the distance x, in the direction of the debris' flow, from the toe of the slope to the depositional area. Similarly, the distance from the slope to the tip of the saltating particles, defined to be the maximum runout distance, is denoted L_{max}. Since the total mass of saltating particles was less than 1% of the collapse weight, our study focused on the runout distance L_d in evaluating the area where the granular materials collide as a group with a large mass.

3.4.2 Granular flow velocity

The velocity vector of the granular avalanche has been calculated from the 500 fps images using PIV analysis. Then, time waveforms of the measured velocity were taken, shown by the red frame in Fig. 5.

4. INFLUENCE OF GRANULAR DIAMETER ON RUNOUT DISTANCE

4.1 Final Deposition Shape

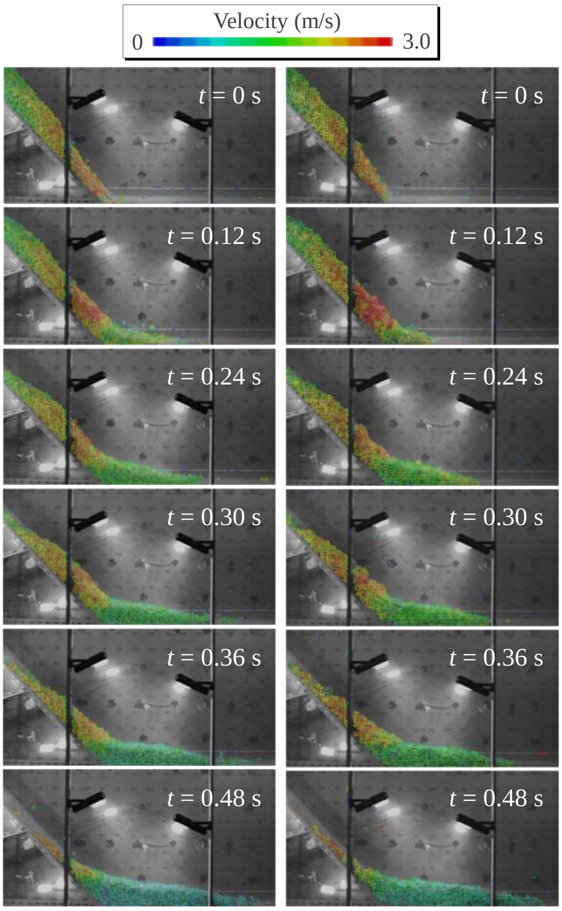
Fig. 6, Fig. 7, and Fig. 8 show the final deposition shapes summarised for each slope angle θ = 30, 45, and 60°, respectively. There is no significant difference in the depositional shape at a slope height of H = 0 mm. A possible reason for the small effect of granular diameter is that the flow height of H = 0 mm is a test condition that only collapses as in the dam-break type angle of repose test, and the short flow distance reduces the number of collisions between granular materials. At slope height H = 400 and 800 mm, materials with larger granular diameters tend to increase the runout distance under conditions when the slope angle θ = 30° or 45°. This trend is consistent with results of previous studies [5] which show a positive association between runout distance and granular diameter. However, when the slope angle θ = 60°, large rock masses do not attain their true maximal runout distance, which is disagreement with the previous result [5].

4.2 Distribution of Flow Velocity

In contrast to the previous finding that the larger the granular diameter, the longer the runout distance [5], the flow velocity distribution of granular avalanches was investigated to clarify why the debris with large granular diameter do not maximise the runout distance when the slope angle θ =60°.

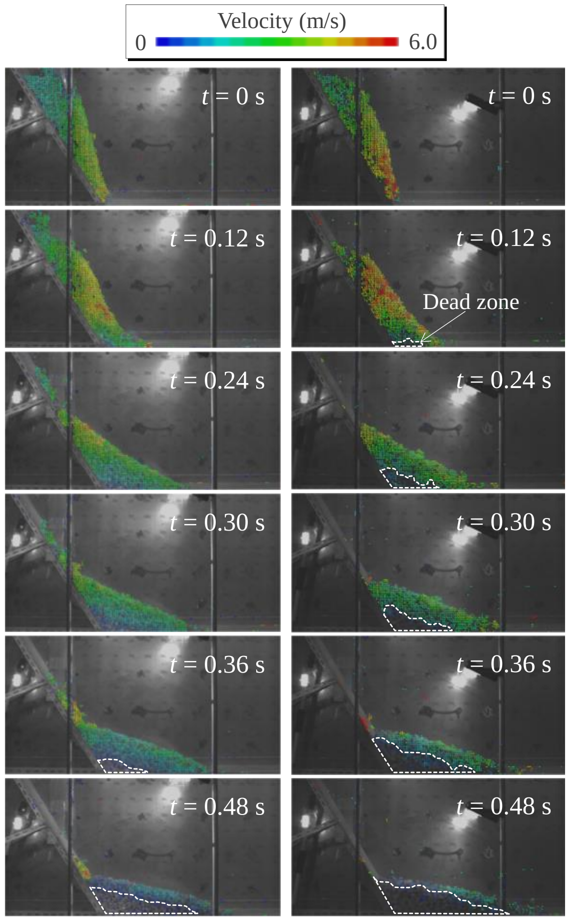
First, we focus on the case when the slope angle θ = 45° and height H = 400 mm, as the flow behavior under these conditions corroborate existing results that longer runout distances coincide with larger granular diameters. Fig. 9 shows the distribution of flow velocity for both medium and large granular material. This distribution suggests that the thickness of the flow layer tends to become thicker as granular diameter increases. The reason for the positive association between runout distance and granular material may be that the momentum of granular materials pushing on granular materials previously settled at the slope's toe increases alongside particle mass, and, with larger materials, the velocity is less likely to decrease as the thickness of the deposited layer increases; in addition to these speculations, there is existing literature showing that avalanches involving larger particles exhibit fewer collisions per particle [19].

We now turn our attention to the case θ = 60°, H = 400 mm, where the large granular material did not



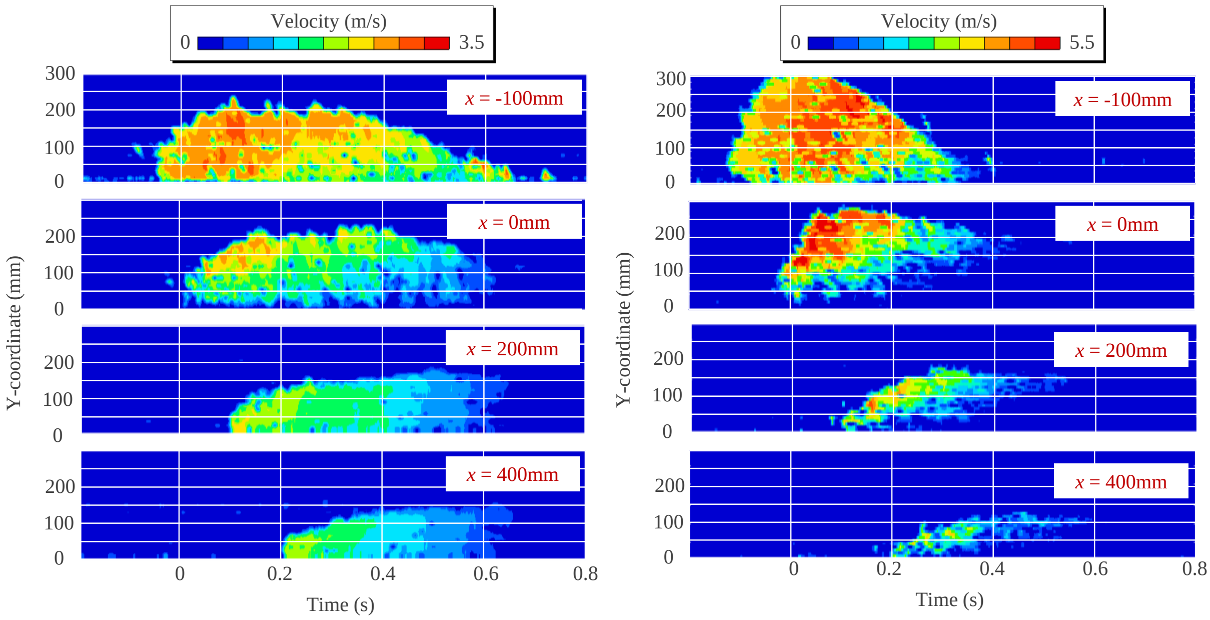
(a)Medium (Case 14) (b) Large (Case 15)

Fig. 9 Velocity distribution: θ = 45° and H = 400 mm



(a)Medium (Case 23) (b) Large (Case 24)

Fig. 10 Velocity distribution: θ = 60° and H = 400 mm



(a) θ = 45°(Case 15) (b) θ = 60° (Case 24)

Fig. 11 Time contours of flow velocity: H = 400 mm (large granular material)

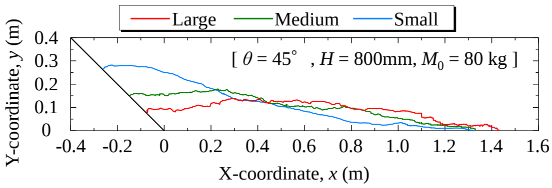


Fig. 12 Final deposition shapes: θ = 45°, H = 800 mm, and M_0 = 40 kg × 2 (Cases 31–33)

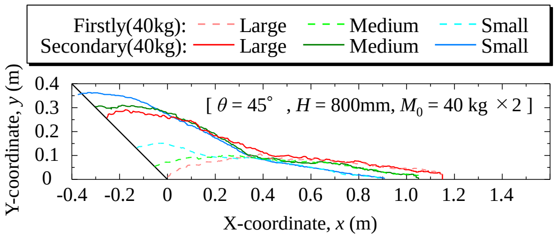
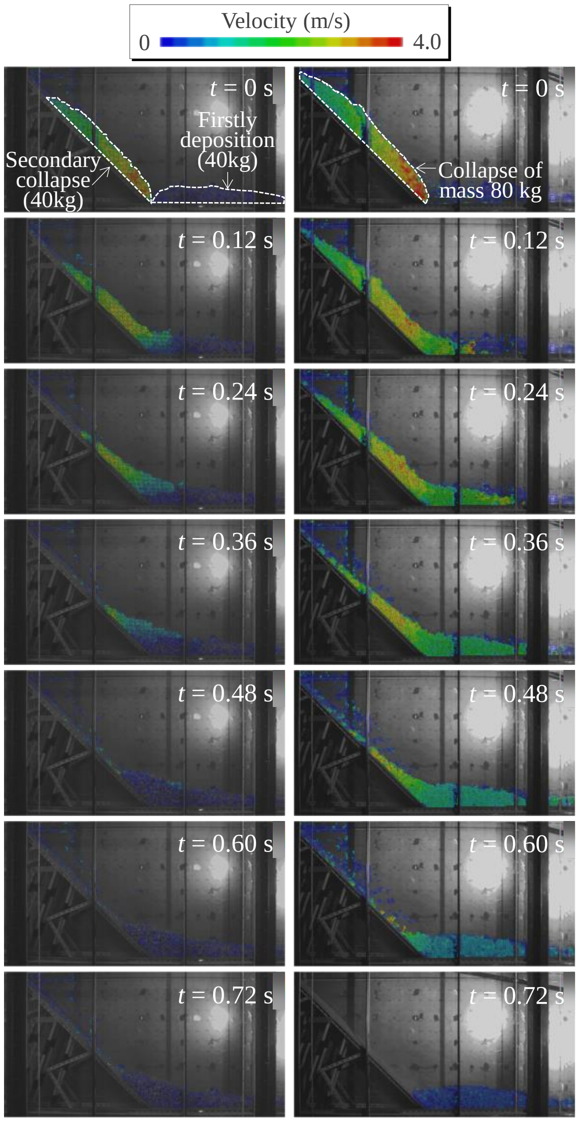


Fig. 13 Final deposition shapes: θ = 45°, H = 800 mm, and M_0 = 80 kg (Cases 28–30)

have the maximum runout distance, in defiance with the expected result. Fig. 10 shows the flow velocity distribution for both medium and large granular material under these conditions. For the large granular material, a dead zone immediately occurs after the granular avalanche impacts the horizontal plane, where the velocity near the toe of the slope nearly goes to zero. In particular, the dead zones of large granular material occur earlier than those of medium granular material, indicating that larger dead zones have a wider developmental area than those created by medium granular material.

Fig. 11 shows time contours of flow velocity for medium and large granular materials at θ = 60°. The vertical and horizontal axes exhibit the vertical layer thickness and the time, respectively. In the figures, we identify t = 0 s as the moment when the leading edge of the granular avalanche impacts the horizontal plane. These figures indicate that the occurrence of the dead zone is not instantaneous, but rather is a continuous phenomenon occurring immediately after the impact of the granular avalanche on the horizontal plane.

Comparing Fig. 9 and Fig. 10, at θ = 45°, where no dead zone develops, the granular materials on the horizontal plane x ≥ 0 have a small velocity gradient from the bottom to the surface, indicating that the sliding mode is such that the preceding granular materials are pushed out by subsequent materials. On the other hand, when θ = 60°, and a significant dead zone develops, the granular materials on the horizontal plane have a large velocity slope angle from the bottom to the surface, and the mode indicates that the following granular materials overtake the preceding granular materials in the vicinity of the toe of the slope.



(a)Case 33 (b) Case 30

Fig. 14 Velocity distribution: Large, θ = 45° and H = 800 mm

4.3 Secondary Slope Failure

Fig. 12 shows the final depositional shape of the experimental case, in which 40 kg of granular material collapsed at a slope angle of θ = 45° and slope height of H = 800 mm, followed by 40 kg of granular material. Fig. 13 shows the final depositional shape for a slope angle θ = 45°, slope height H = 800 mm, and collapse mass M_0 = 80 kg. The experimental conditions in Fig. 12 and 13 were for a total collapse mass of 80 kg. Fig. 14 shows the distribution of the flow velocity for Figs.12 and 13.

The first slope failure resulted in a longer runout distance for larger granular diameters, illustrated by the results of Fig. 7 when the slope height H = 800 mm. On the other hand, for secondary slope failure, the runout distance was not longer than that attained by the first, regardless of the granular diameter. This may be because the granular materials deposited in the first collapse increased the roughness of the toe of the slope, thus increasing its frictional resistance.

Both experimental conditions in Fig. 12 and Fig. 13 are for a total collapse mass of 80 kg. It can be seen from this that an 80 kg collapse at one time has a greater runout distance than a collapse divided into primary and secondary slope failures. As discussed in Fig. 9, this may be due to the possibility that the runout distance is greater under the condition where the slope failure occurs all at once due to the greater thickness of the flow layer.

5. CONCLUSIONS

In this study we investigated the effect of the granular diameter on the runout distance based on the comparative examination of the test results. The observed behavior can be summarised as follows:

1) The observed runout behavior of rock debris in accordance with previous findings revealed that the rock debris with a larger grain diameter have a larger runout distance.
2) In the case of the sliding mode, in which the flowing rock debris act to push out those deposited at the toe of the slope, the change in the flow layer thickness of rock debris with different grain diameters contributes to the velocity decay on the horizontal plane and may be an important parameter in the prediction of the runout distance.
3) The runout distance does not increase with increasing granular diameter when a dead zone is developed at the toe of the slope, which is a mode where the preceding granular materials are overcome by those following.
4) In the slope failure in which the same rock debris volumes flow separately in two steps, primary and secondary slope failures, the runout distance of the secondary slope failure is not larger than that of the primary slope failure, regardless of the granular diameter.
5) Even if the total collapsing volume is same, the runout distance grew in the case when the entire mass collapsed instantaneously.

6. ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support provided by the Japan Society for the Promotion of Science (Grant-in-Aid for Young Scientists 21K14239) and the Toyohashi University of Technology (Grant-in-Aid for activating education and research).

7. REFERENCES

[1] Zhang S., and Zhang L., Assessment of human risks posed by deadly debris flow in the Wenchuan earthquake area, International Journal of GEOMATE, Vol.8, No.1, 2015, pp.1207-1211.

[2] Cundall P. A., and Stack O. D. L.: A Discrete Models for Granular Assemblies, Geotechnique, Vol.29, No.1, 1979, pp.47-65.

[3] Nakase H., Iwamoto T., Cao G., Tabei K., Sakaguchi H., and Matsushima T., Reproduction analysis of actual slope collapse and parametric study for evaluation of the deposit volume by a simple model of distinct element method, JSCE Journal of Earthquake Engineering, Vol.73, No.4, 2017, pp.694-703.

[4] Nakase H., Cao G., Tochigi H., and Tabei K., A method to access collision hazard of falling rock due to slope collapse application of DEM on modeling of earthquake triggered slope failure for nuclear power plants, JSCE Journal of Earthquake Engineering, Vol.71，No.4，2015，pp.476-492.

[5] Tochigi H., Investigation of Influence of Falling Rock Size and Shape on Traveling Distance due to Earthquake, Civil Engineering Research Laboratory Rep., 2010, N09021.

[6] Li K., Wang YF., Lin QW., Cheng QG., and Wu Y., Experiments on granular flow behavior and deposit characteristics: implications for rock avalanche kinematics, Landslides, Vol.18, 2021, pp.1779-1799.

[7] Bartali R., Rodríguez Liñán G.M., Torres-Cisneros L., Pérez-Ángel G., and Nahmad-Molinari Y., Runout transition and clustering instability observed in binary-mixture avalanche deposits, Granular Matter, Vol.22, No.30, 2020.

[8] Duan Z., Wu YB., Peng JB., and Xue SZ., Characteristics of sand avalanche motion and deposition influenced by proportion of fine particles, Acta Geotechnica, Vol.18, 2023, pp.1353–1372.

[9] Lu K., Chen Y., and Wang L., A study on the motion and accumulation process of non-cohesive particles. Natural Hazards, Vol.105, 2021, pp.205–225.

[10] Mollon G., Richefeu V., Villard P., and Daudon D., Discrete modelling of rock avalanches: sensitivity to block and slope geometries, Granular Matter, Vol.17, No.5, 2015, pp.645-666.

[11] Watanabe D, Moriguchi S., and Terada S., Effect of particle size distributions on granular flow simulations using discrete element method, JSCE Journal of Geosphere Engineering, Vol.77, No.4, 2021, pp.392-402.

[12] Cheng Y.M., Fung W.H.I., Li L. and Li N., Laboratory and field tests and distinct element analysis of dry granular flows and segregation processes, Nat. Hazards Earth Syst. Sci., Vol.19, 2019, pp.181-199.

[13] Yu F., and Su L., Experimental investigation of mobility and deposition characteristics of dry

granular flow, Landslides, Vol.18, 2021, pp.1875-1887.

[14] Li H., Duan Z., Wu Y., Dong C. and Zhao F., The motion and range of landslides according to their height, Frontiers in Earth Science, Vol.9, 2021, Article 736280.

[15] Bryant S.K., Take W.A., and Bowman E.T., Observations of grain-scale interactions and simulation of dry granular flows in a large-scale flume, Canadian Geotechnical Journal, Vol.52, 2015, pp.638-655.

[16] Zhou G.G.D., and Sun Q.C., Three-dimensional numerical study on flow regimes of dry granular flows by DEM, Powder Technology, Vol.239, 2013, pp.115-127.

[17] Zingg T., Beitrag zur Schotteranalyze, Schweizerische Mineralogische und Petrographische Mitteilungen, Vol. 15, 1935, pp. 39-140.

[18] Naito N., Matsuda T., Miura K., and Omura T., Three-dimensional discrete element modelling of granular avalanche under multiple flow conditions, International Journal of GEOMATE, Vol.24, Issue 106, 2023, pp.77-84.

[19] Naito N., Yoshida I., Nakase H., and Tochigi H., Probability Distribution of Falling Rock by Experiments and a Method to Assess Collision Hazard, 6th International Conference on Earthquake Geotechnical Engineering, 2015, Paper No.279.