The influence of particle size on the spread distance and angle of friction of granular materials

Chyan-Deng Jan, and Litan Dey*  
Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Taiwan

Abstract. To produce a hazard map and thus provide mitigation measures against natural catastrophic events such as landslides, avalanches, and debris flows, it is necessary to determine the spread distance of such flows. There is a well-documented relationship between the angle of friction and the debris flow volume, allowing one to determine the possible distance a debris flow can travel. However, the effect of mean particle size ($d_{50}$) and the sorting coefficient ($S_c$) on the final spread distance ($D_f$) has received mere attention. In this study, a mini conical-shaped mould was used to measure the final spread distance ($D_f$) and angle of friction ($\alpha_f$) for various dry granular material samples both in air and in water. Experimental results indicated that a granular material sample with a smaller $d_{50}$ travel a longer distance compared to a sample with a higher $d_{50}$. However, a sample with a smaller $d_{50}$ results in a smaller angle of friction than the one with a higher $d_{50}$. Conversely, a well-sorted sample has a smaller spread distance and larger angle of friction. Results also indicated that the spread distance in air is slightly larger and the angle of friction is slightly smaller than in water.

1 Introduction

Granular flows, propelled by gravity, occur often on the surfaces of Earth and other planets. They are composed of solid particles that have been often mixed with an interstitial lighter fluid (liquid or gas) which may interact with the particles to reduce the intensity of their interactions and hence boost the likelihood of propagation. Landslides, avalanches (of rock, snow, or water), debris flows, and volcanic events like pyroclastic flows and debris avalanches are all examples of these types of granular flows. These kinds of disastrous events are also witnessed underwater, such as submarine landslides, which can cause tsunamis, damage underwater infrastructure, and even cause coastal geomorphological changes [1-2]. Even though these natural disasters got a lot of attention from scientists, they are still hard to understand on a physical level [3-4]. The prediction of their final spread distance remains a top priority among the numerous challenges induced by these flows, largely because of the obvious concern caused by their destructive power. Interestingly, these types of flows can travel a distance that is several times larger than the height of the source topography [5]. The ratio between the vertical fall height and the horizontal spread distance is known as the angle of friction ($\alpha_f$) [6-7]. For loose granular material, the angle of friction is generally equal to the angle of repose. However, if the material is compacted this relationship is no longer valid.

As documented by several field observations, granular debris flows include a broad range of particle sizes, from boulders and gravel to silt and clay. For debris flow, the mean particle sizes ($d_{50}$) are in the range of 2 to 200 mm with a typical uniformity coefficient ($C_u = d_{60}/d_{10}$) in the range of 100 to 1000 [8-9]. Particle size distribution of granular materials along with their two parameters uniformity coefficient ($C_u$) and sorting coefficient ($S_c = \sqrt{d_{75}/d_{25}}$), are often used to represent the gradation of those material samples [10-11]. Dry granular sand with $C_u > 6.0$ is generally referred to as a well-graded or non-uniform, while $C_u < 4.0$ is characterized as a poorly graded or uniformly graded sample. According to Trask [11], the deposit is well-sorted if $S_c < 2.0$, poorly sorted if $S_c > 4.5$, and normally sorted if $2.0 \leq S_c \leq 4.5$. Different variables influence the physical properties of these granular materials, such as material composition, particle size distribution, particle shape, mass density, and other properties [12, 13, 14]. It is very difficult to determine the physical properties of such granular materials. Conversely, there are implicit links between particle size distribution and the physical properties of granular material [15]. Understanding the physical behavior of granular debris flow requires finding these implicit relationships. Few studies explicitly studied the effect of mean particle size ($d_{50}$) and sorting coefficient ($S_c$) on the flow behavior of granular material [8]. However, the effect of $d_{50}$ and $S_c$ on the final spread distance ($D_f$) and angle of friction ($\alpha_f$) of such flows in water has received mere attention. In this study, a mini conical-shaped mould was used to understand the effect of $d_{50}$ and $S_c$ on the physical properties of various granular material samples both in air and in water.

* Corresponding author: litanwre@gmail.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).
2 Materials and experimental procedure

2.1 Granular material samples

This investigation presents four different samples of granular materials, and their particle size distribution is shown in Fig. 1. To evaluate the particle size distribution and other parameters of each material sample, 900 grams of material with a particle density of 2.65 g/cm\(^3\) were used. Table 1 displays the mean particle size \(d_{50}\), uniformity coefficient \(C_u\), and sorting coefficient \(S_c\) for each material sample. Samples 2 and 3 have \(S_c < 2.0\), indicating well-sorted samples, while samples 1 and 4 are normally sorted (2.0 < \(S_c < 4.5\)). In other words, samples 1 and 4 are well-graded or non-uniform (\(C_u > 6.0\)), while samples 2 and 3 are poorly graded or uniform (\(C_u < 4.0\)). The Corey shape factor (SF) of 15 randomly chosen particles from each sample was measured using a digital caliper, and their average SF varied from 0.40 to 0.62. (Table 1).

![Fig. 1. Particle size distribution of the tested samples](image)

Table 1. Material properties of the tested samples. The unit of different particle sizes are in 'mm'.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SF</th>
<th>(d_{10})</th>
<th>(d_{25})</th>
<th>(d_{50})</th>
<th>(d_{60})</th>
<th>(d_{75})</th>
<th>(C_u)</th>
<th>(S_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.51</td>
<td>0.052</td>
<td>0.14</td>
<td>0.31</td>
<td>0.38</td>
<td>0.59</td>
<td>7.34</td>
<td>2.06</td>
</tr>
<tr>
<td>2</td>
<td>0.40</td>
<td>0.238</td>
<td>0.30</td>
<td>0.40</td>
<td>0.46</td>
<td>0.61</td>
<td>1.95</td>
<td>1.44</td>
</tr>
<tr>
<td>3</td>
<td>0.62</td>
<td>0.430</td>
<td>0.46</td>
<td>0.51</td>
<td>0.53</td>
<td>0.56</td>
<td>1.23</td>
<td>1.10</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
<td>0.026</td>
<td>0.07</td>
<td>0.26</td>
<td>0.34</td>
<td>0.49</td>
<td>12.93</td>
<td>2.76</td>
</tr>
</tbody>
</table>

2.2 Slump test procedure in air

Several researchers employed the slump test to evaluate concrete flow ability and consistency. As described by Jan et al. [16] and Jan and Dey [17], a downscaled conical-shaped mould was employed in this study for conducting the slump test. The top inner diameter of the mould is \(d_0 = 50\) mm, the bottom inner diameter is \(D_0 = 100\) mm, and the height is \(H_0 = 150\) mm (Fig. 3a). A rectangular water tank of 60 cm long, 60 cm wide, and 40 cm in height was constructed (Fig. 2). Perspex glass with a thickness of 0.5 cm was used to construct the water tank. One person holds the slump mould in the middle of the horizontal plane of the empty tank while another pours the material sample into the mould. The sample material is poured in three layers into the mould, then tamped 25 times with a steel rod to insure that as little segregation as possible occurred during sample preparation. The ends of the steel rod are rounded, and tamping was performed using the rod uniformly throughout all three layers. Then, at a suitable speed, vertically remove the mould and allow the sample to spread. The lifting speed of the mould may influence the slump-flow test results. As a result, in this investigation, the lifting velocity of the mould was maintained as slow and steady as possible for each experiment. The human hand lifting speed of the mould is often substantially less than 1 m/s, and lifting speeds below 10 m/s had no discernible effect on the final slump-flow results [18]. Figure 3 displays a schematic illustration of the slump test procedure. For various material samples, two primary variables are measured by using a laser distance meter, the final height of the deposit and the final spread distance as shown in Fig. 3c. The spread distance of the deposit is measured in two perpendicular directions, and the final spread distance (\(D_f\)) for each sample is given as the average of the two measurements. Similarly, the average of three measurements for height was used to get the final height \(H_f\). The dimensionless form of the final spread distance was written as \(D_{fs} = D_f/D_0\), where \(D_0\) is the bottom diameter of the initial sample (i.e. 100 mm in this study).

![Fig. 2. Experimental setup of the slump test](image)

![Fig. 3. Schematic of the slump test procedure](image)

2.3 Slump test procedure in water

After carefully positioning the mould in the middle of the bottom plane of the empty water tank and filling it with the sample to be tested, the water tank is filled with water to a depth of 30 cm, which is twice the height of the slump mould. To prevent causing turbulence or waves in the tank, the slump mould was lifted very gently and slowly. Wait for a considerable amount of time (roughly 2 to 3 mins) to allow any suspended materials to settle. The final height (\(H_f\)) and the spread distance (\(D_f\)) was measured by moving a ruler along the scaffold (Note: underwater, a ruler is employed instead of a laser distance meter since the laser distance meter used in this investigation is not suitable to be used underwater). Similar to the measurements in air, the final spread distance is the average of two perpendicular readings and the final height is the average of three readings [16].
3. Results and discussions

3.1 Final deposit profiles

Figure 4 represents the final profiles of deposits for various material samples and their two parameters, final height $H_f$ and final spread distance $D_f$ are measured. It can be observed from Fig. 4 that sample with a larger $d_{50}$ produces a lower spread and greater height of the final deposits and vice-versa. Similar behavior was also observed for all the material samples when the slump test was conducted in water. However, the final height and spread distance in water for a given $d_{50}$ was found to be slightly smaller than that of in air. A comparison of the final deposit profile for $d_{50} = 0.51$ mm in both air and water is shown in Fig. 5.

Based on the measured $H_f$ and $D_f$, the angle of friction of each material sample was determined and is defined in Eq. 1.

$$\alpha_f = \tan^{-1}\left(\frac{2H_f}{D_f}\right)$$ (1)

Using this method (Eq. 1), the angle of friction is the base angle of an idealized cone produced by linking the top and bottom points of the deposit body as shown in Fig. 6. Previously Dong et al. [19] have used this method to determine the angle of friction. In the above Eq. 1, the unit of $\alpha_f$ is in radian.

3.2 Influence of mean particle size on final spread distance and angle of friction

The influence of mean particle size $d_{50}$ on the dimensionless final spread distance $D_{f*}$ is shown in Fig. 7a. Based on the results of the present study, the spread distance reduces as the $d_{50}$ of the samples increases, i.e. material samples with smaller $d_{50}$ have a larger spread distance and vice versa (Fig. 7a). Results obtained in water revealed that the spread distance in water seems to be influenced by the water environment and is somewhat shorter than that in air (Fig. 7a). In other words, granular material sample with the same $d_{50}$ travels farther in air than in water. On the other hand, the $d_{50}$ has a significant impact on the angle of friction of granular material samples. A sample with a smaller $d_{50}$ yields a gentler angle of friction, while a sample with a larger $d_{50}$ produces a steeper angle of friction (Fig. 7b). Comparing the results in air to those in water, the angle of friction underwater is somewhat found to be larger.

3.3 Influence of sorting coefficient on the final spread distance and angle of friction

Figure 8a&b shows the influence of the sorting coefficient on the final spread distance and angle of friction. In general, lower spread distance and larger angle of friction can be observed for a well-sorted sample or a sample with a low sorting coefficient (i.e. $S_c < 2.0$). For the present study, normally sorted samples (i.e. samples 2 and 3) show larger spread distances and smaller angle of friction. Figure 8a&b also reveals that for the same sorting coefficient, granular flows in air have a larger spread distance than in water, whereas the angle of friction in air is lower than in water.
As seen in Figs. 7 and 8, the final spread distance and angle of friction vary in air and water. The following points may help to explain these differences:

(i) The granular flows in air have a longer spread distance than that of corresponding flows in water due to a reduction in effective gravity in the water environment [20].

(ii) According to Francesca et al. [21], due to the capillary action of water, negative excess pore pressure builds up in water. This has a direct impact on how grains interact in granular flow, which may significantly reduce granular flow mobility in water.

Figure 7b illustrates that the angle of friction increases as the $d_{50}$ increases, which contradicts the results of Jan [22] and Grasselli and Herrmann [23]. Their findings for homogenous glass sphere mixtures show that the angle of friction decreases with the $d_{50}$. These variations might be caused by differences in sediment shape factors (Table 1).

4 Conclusions

The following conclusions may be inferred from the present experimental results and analyses:

(i) A sample of granular material with a smaller mean particle size ($d_{50}$) travels farther than one with a larger $d_{50}$.

(ii) The angle of friction of a sample with a lower $d_{50}$ is smaller than the sample with a higher $d_{50}$.

(iii) The spread distance is shorter for a sample with a low sorting coefficient ($S_c$), but the angle of friction is higher.

(iv) The spread distance of granular material samples in water is slightly shorter than that in air. While the angle of friction in water is slightly higher than that in air.

These results demonstrated that thorough laboratory studies may provide insight into the physical properties of granular debris flow on land as well as underwater. Further investigations are required to understand how the particle size distribution and sorting coefficient influence the final spread distance and angle of friction when both $d_{50}$ and $S_c$ vary individually. In addition, it is recommended that the influence of bottom roughness, interstitial fluid density, and particle shape on the physical parameters of such flows be investigated.

This experimental work was conducted in the Hydraulic Laboratory of the National Cheng Kung University, Taiwan, and financially supported by the National Science and Technology Council, Taiwan (NSTC–110–2221–E–006–062).

References

5. W. Brian Dade, H.E. Huppert, Geology 26, 803-806
6. A. Heim, Bergsturz und menschenleben, Fretz & Wasmuth 77, 218 (1932)
7. A.E. Scheidegger, Rock mechanics 5, 231-236 (1973)