Smoothed Particle Hydrodynamics Modeling of Granular Column Collapse

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ABSTRACT

Granular column collapse is a commonly studied granular flow problem, where an initially cylindrical column of dry granular materials collapses onto a flat surface under gravity. In this study, the meshless method Smoothed Particle Hydrodynamics (SPH) is used to model this phenomenon examining in particular the effect of aspect ratio, defined as the ratio of the initial height h_0 and radius r_0 of granular column. The numerical results are consistent with experimental results in terms of three aspects: (1) description of flow shapes; (2) runout distance and (3) final deposit height. Further observations and measurements are obtained to explore the collapse.

KEYWORDS: granular column collapse, aspect ratio, Smoothed Particle Hydrodynamics

1 Introduction

Collapse of granular media, a very common phenomenon in nature (e.g. landslides) and industry (e.g. agriculture, pharmaceutics), has the risk to cause serious injury and property damage if not properly managed. Therefore, it is crucial to understand mechanisms such as their travelling distance, so that appropriate measures can be taken to mitigate the risk.

A number of studies have examined the spreading of collapsing columns of sand or other granular materials on a flat surface using both experimental [1-3] and numerical methods [4] as a relatively simple experiment to carry out that still allows capturing complex behaviour. As a meshless method, the Smooth Particle Hydrodynamics (SPH) method has been widely used to deal with large deformation problems. Currently, many researchers focus on method-related developments [5-7], where experiments of granular column collapse have been mainly used to validate the models.

In this paper, we also first validate the SPH method implemented in the software LS-DYNA used to model sand columns collapse, to then investigate additional behaviour characteristics and parameters of granular column collapse.

2 SPH granular column model

The geometry of the granular column filled with cohesionless sandy soil is shown in Figure 1. The aspect ratio a is defined as the ratio of initial height h_0 and initial radius r_0. Gravity (9.80 m/s^2) was applied after the soil creation to cause free collapse of the column. In experiments, a container is typically used to prepare the column, which is then lifted up to initiate soil collapse. This may cause non-negligible boundary condition effect that we are not investigating here. The column is placed in a rectangular domain large enough to include the column runout using the *DEFINE_BOX keyword. A rigid wall was created using *RIGIDWALL_PLANAR at the bottom. The friction coefficient (FRIC) between the SPH particles and the rigid wall was set to 0.4 to imitate real conditions [8]. For the soil, the SPH particle spacing was set to 3 mm.

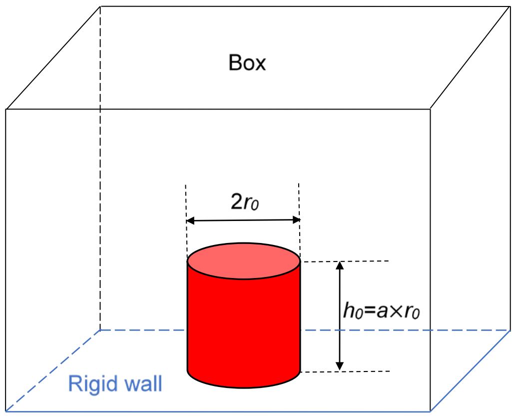

Figure 1: Initial SPH-based granular column model in LS-DYNA

The material card *MAT_MOHR_COULUMB (*MAT_173), which is based on the Mohr-Coulomb failure criterion, was adopted to simulate the soil. This material card was selected due to its suitability to simulate cohesionless sandy soil, which was hard to achieve using other materials that can also be adopted to model soils, e.g. *MAT_SOIL_AND_FOAM (*MAT_005) and *MAT_FHWA_SOIL (*MAT_147). The parameters used for this material are shown in Table 1. [1] reported the angle of repose of the sand used in their experiments is 30°. However, in SPH-based granular column collapse simulations, it has been shown that using 30° as the friction angle of the sand material overestimated runout distance after the collapse [Ref that showed this], thereby 37° has been used by many researchers and shown to obtain satisfactory results [5, 6, 9]. Thus, in our simulations the friction angle of the sand material was also set as 37°. The dilation angle was set to ψ=0 following other granular column modelers [6, 10, 11].

*Table 1: Parameters adopted for the material card *MAT_MOHR_COULUMB (*MAT_173)*

Parameter	**Description**	**Sands**
RO	Mass density	2600 kg/m^3
GMOD	Elastic shear modulus	2.310e6 *Pa*
RUN	Poisson's ratio	0.3
PHI	Angle of friction	37°
CVAL	Cohesion value	0.0
PSI	Dilation angle	0.0

A series of granular column collapse simulations were run varying aspect ratios by changing the initial column height h_0 while maintaining the initial column radius r_0. Table 2 summarizes the basic information for the simulations.

Table 2: Simulation program of 3D granular column collapses

Case ID	**h_0 /m**	**r_0 /m**	**$a = h_0/r_0$**	**No. of SPH particles**
1	0.055	0.1	0.55	63,378
2	0.09	0.1	0.9	105,630
3	0.15	0.1	1.5	176,050
4	0.275	0.1	2.75	323,932
5	0.4	0.1	4	471,814
6	0.6	0.1	6	704,200
7	0.9	0.1	9	1056,300
8	1.38	0.1	13.8	1619,660

3 Model validation

3.1 Granular flow patterns

Figure 2 shows the evolution of column collapse observed in the SPH models with three representative aspect ratios including small (*a*=0.55), intermediate (*a*=2.75) and large (*a*=13.8) values. The final flow patterns experimentally reported by [1] for the three aspect ratios are given for validation purposes. The SPH results are in good agreement with the experiments. For small aspect ratios (e.g. *a*=0.55), the final pattern has a flat surface on the top. For intermediate aspect ratios (e.g. *a*=2.75), the top surface changes from a flat plate to a tip. For large aspect ratios (e.g. *a*=13.8), the collapse flow forms a concentric wave at the final deposit. There is a lower concentric zone between the wave and the central static grains, as has been clearly observed in the numerical result at t=924ms. However, this lower zone is not so obvious in the experiments.

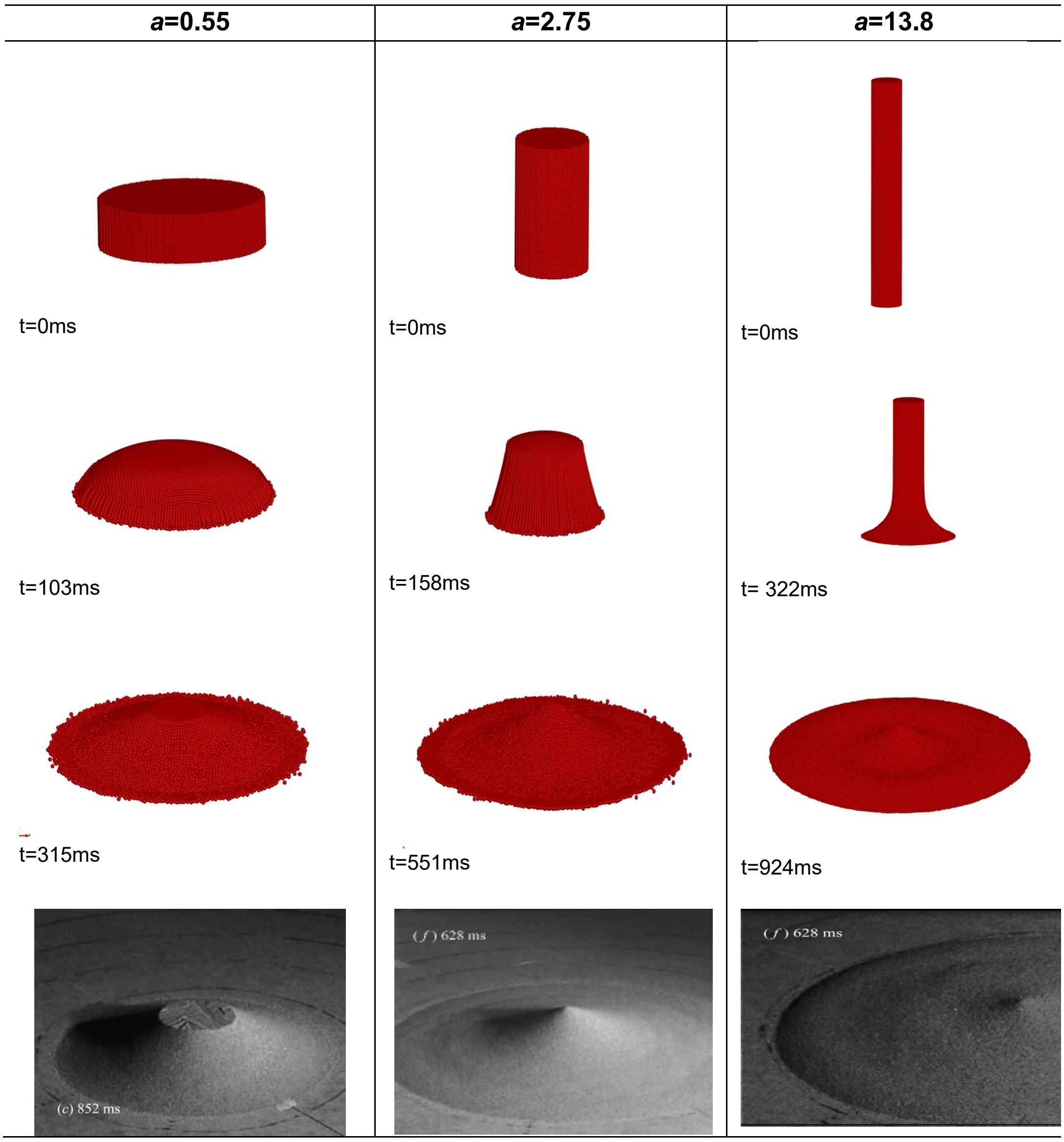

Figure 2: Granular column collapse evolution at various time points observed in three columns with representative aspect ratios (small to large from left to right, colored images) and finial experimental collapse patterns reported in [1] (grey images).

3.2 Runout distance

The relationship between the final runout distance r_∞ in a non-dimensional format and initial aspect ratio, was proposed by Lube et al., (2004) by fitting experiments, as given in equation (1).

$$\frac{r_\infty - r_0}{r_0} = \begin{cases} 1.24a, a < 1.7 \\ 1.6a^{1/2}, a \geq 1.7 \end{cases} \quad (1)$$

During the process of granular column collapse, some of the SPH particles move far away from the main collapse body, leading to ambiguity when measuring the finial runout distance. To overcome this problem, the method given by [12] was used, which proposed the concept of effective runout distance. The effective runout distance is determined by the model final deposit continuous domain. A virtual measurement circle representing the effective runout distance is used to determine this continuous domain in software.

The experimental [1] and numerical results of the granular column collapse are given in Figure 3. It can be seen that the numerical results again match well with the experiments. The larger the aspect ratio, the longer the runout distance will be. The final runout distance values against aspect ratio have two areas. For small aspect ratio (a<1.7, reported by Lube et al.,2004), the runout distance has a linearly increasing trend; whereas for bigger aspect ratio (a>1.7, reported by Lube et al.,2004), the runout distance increase trend slows down and changes from linear to nonlinear growth as shown in the equation.

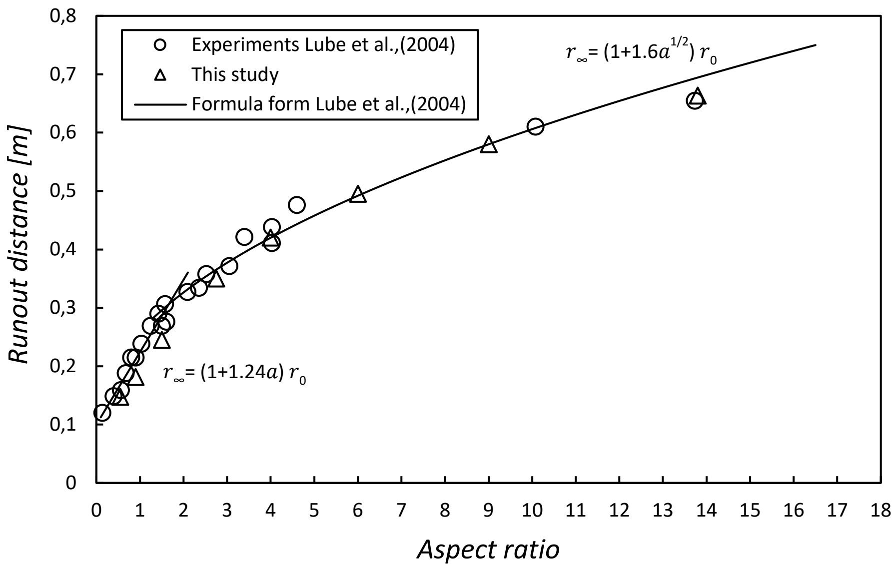

Figure 3: Comparison of final runout distance between SPH simulations and experiments in [1]

3.3 Final height

The non-dimensional experimental relationship for the final deposit height proposed by Lube et al., (2004) is given in equation (2) which depends on the aspect ratio and initial height.

$$\frac{h_\infty}{r_0} = \begin{cases} a, 0 \leq a < 1.0 \\ 0.88a^{1/6}, 1.0 \leq a < 10 \end{cases} \quad (2)$$

Figure 4 illustrates a comparison of the final deposit height h_∞ against aspect ratio between SPH simulations and experimental results. The axes are plotted in logarithmic scale. The results for the final height are consistent with the experimental results. There are also two stages in the final height plot. The transition point (equation (2)) is at *a=1*. For $a < 1$, the final height shows a fast linear increase with the aspect ratio, demonstrating a significant impact of the aspect ratio on the final height; for $1 \leq a < 10$, the final height still follows a linear increase trend, but with a lower increasing slope. At this stage, the aspect ratio has less influence on the final height. Note that for aspect ratios larger than 10, Lube et al., (2004) did not propose an empirical formula to predict the final height due to limited test amount.

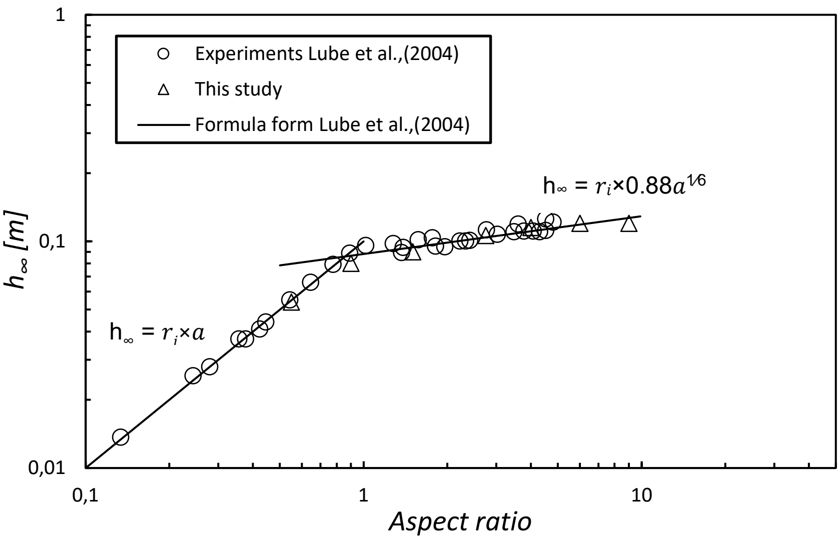

Figure 4: Comparison of final deposit height between SPH simulations and experiments in [1]

4 Further explorations

Figure 5 shows further numerical results from the small column small (*a*=0.55) including resultant displacement field, plastic strain field and energy variation. Figure 5(a) illustrates the resultant displacement accumulated from the beginning of collapse. A clear static region (displacement is almost zero) inside the column is visible. From the plastic strain field shown in Figure 5(b), the strain inside the model is zero, and large strains occur outside of the model. Figure 5(c) shows the energy variation curve, which would be useful to analyse the collapse of granular column from an energetic perspective. The above results can potentially be applied in further studies of granular column collapse.

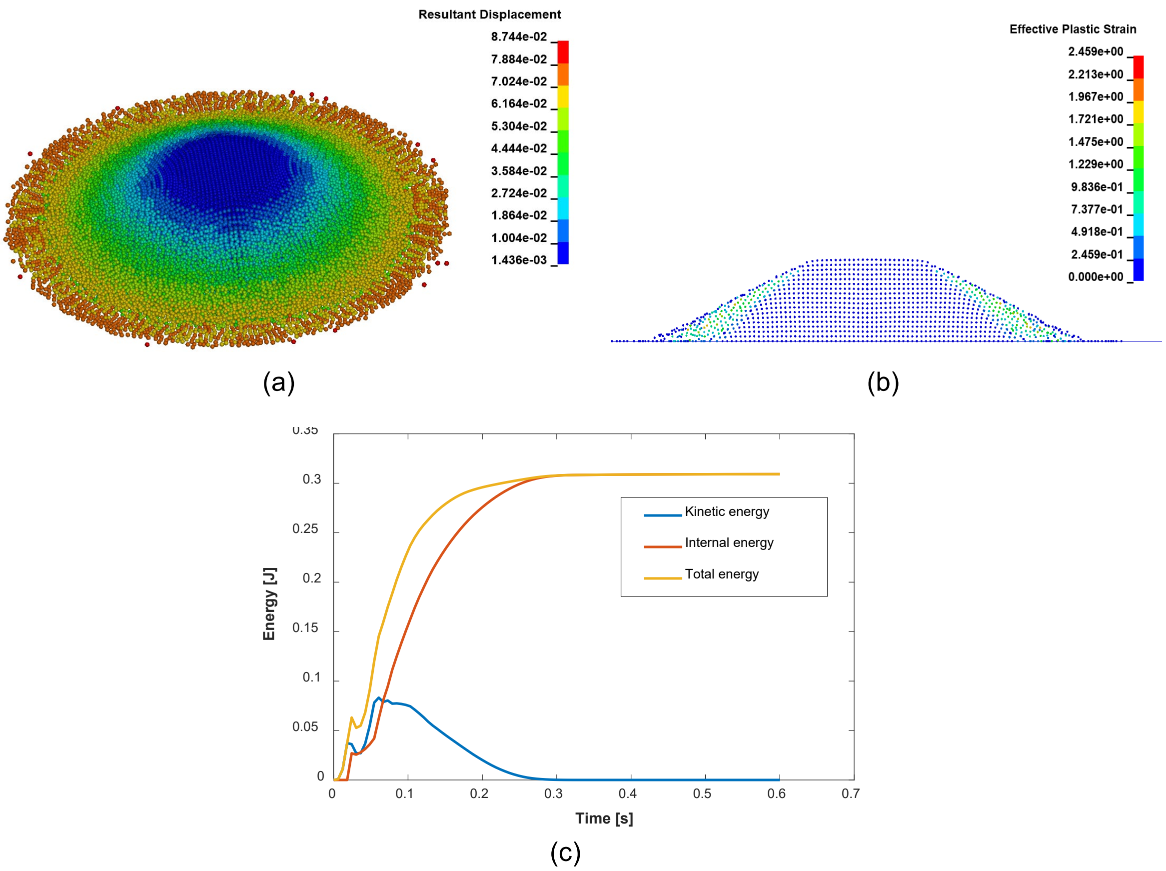

Figure 5: Additional results (a=0.55) (a) *resultant displacement;* (b) *plastic strain; (c)* energy variation with time

5 Summary

In this study, the SPH method implemented in LS-DYNA has been adopted to simulate a granular column collapse for a range of aspect ratios. The numerical results have been verified against experimental evidence from three aspects: (1) description of flow shapes; (2) runout distance and (3) final deposit height. Several further results that are difficult to obtain experimentally were described, such as resultant displacement field, plastic strain field and energy variation. Further studies investigating the effects of fundamental parameters on granular column collapse response are to be performed.

Acknowledgements

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