Numerical modeling on concrete debris ricocheting off sand ground

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Abstract

A numerical study on concrete debris ricocheting off sand ground is presented in this paper. The numerical package ANSYS LS-DYNA is used to model the whole process of the impact of concrete debris on sand ground. A set of formulation is retrieved from the numerical results to predict the ricochet angle and the ricochet velocity in terms of the incident angle and the incident velocity. The debris size effect on the ricochet phenomenon is studied. It is found that for the range of the debris size studied in this paper, the debris size only has very minor influence on the ricochet.

Keywords: Ricochet, Concrete debris, sand, debris size, LS-DYNA.

Introduction

Ricochet phenomenon appears when a hard projectile impacting on a relatively soft target medium with a certain impact condition. In general, the ricochet process could be controlled by the shape, the size, the strength, the launching velocity and the incident angle of the debris as well as the mechanical properties of the target medium (i.e. ground conditions). In the past, most research work has focused on the ricochet of projectiles off water surface and debris with different materials against soft ground. Soliman et al. (1976) studied the impact of steel and duralumin balls on water and dry, fine sand surfaces analytically and experimentally. It was found that for a given medium (e.g. water or sand), there exists a limiting incident angle beyond which ricochet does not occur, regardless of the incident velocity. On the other hand, when the incident angle is less than the limiting angle, there is an upper bound for the incident velocity beyond which ricochet does not occur. This upper bound is usually named as the (upper) critical incident velocity (for that angle). Knock et al. (2004) studied the impact of masonry debris against hard and soft grounds and concluded that the shape of masonry debris is not a major factor affecting the ricochet phenomenon.

Since experiments are costly, time-consuming and limited in obtaining data, numerical simulation is an attractive alternative for studying the high speed impact and ricochet phenomenon. In this paper, a numerical study on concrete debris impact on sand surface is presented. In the current study, numerical simulations were performed by using Arbitrary Lagrangian Eulerian (ALE) formulation with multi-material (MM) models. A total of six types of concrete debris are employed, namely 20mm, 50mm and 80mm ∅ spheres and 40mm, 60mm and 100mm chamfered cubes.

Ricochet of projectiles against water is defined as an impact or a rebound such that at no time was the projectile fully below the water surface (Johnson 1998). However, when using sand as the target medium, it is found that concrete debris is more likely to come out of the sand after an impact (Xu et al. 2013). Furthermore, it is obvious that concrete debris is able to stand on a sand surface, while it sinks when it is placed on a water surface. Hence, the definition of ricochet against water may not be applicable for the present study and a new criterion should be employed to define the ricochet of concrete debris against sand.

Numerical model of impact

All numerical simulation works in this study are carried out by using the commercial software ANSYS LS-DYNA. The Arbitrary Lagrangian Eulerian (ALE) algorithm embedded in ANSYS LS-DYNA is adopted to model the impact process of concrete debris on sand surface. The concrete debris is meshed by a Lagrangian grid as solid, whereas the air and the sand are meshed by an Eulerian grid as fluid. An advance fluid structure interaction algorithm (FSI) is used to model the interaction between the debris and the sand/air.

The material type Mat_Null (Mat 9) in ANSYS LS-DYNA (LSTC 2007) is employed for air. This material type has no shear stiffness or yield strength and behaves as a fluid. The cut-off pressure is set as 0, so that only positive pressure is considered. The equation of state (EOS) for air is expressed as $p=0.4E(\rho/\rho_0)$, where p is the pressure, ρ is the current density, ρ_0 is the reference density which is taken as $\rho_0=1.29\text{kg/m}^3$ (density of air) and E is the initial internal energy which is taken as $E=2.5\times10^5\text{Pa}$.

The Material Type 16 (Mat 16) in ANSYS LS-DYNA (Livermore Software Technology Corporation 2007) is used to model the concrete behavior. The Mat 16 Mode II provides an automatic internal generation of a simple model for concrete. The material property for concrete debris is taken as: density $\rho_c = 2400\text{kg/m}^3$, shear modulus $G = 3.414\times10^{10}\text{Pa}$ and Poisson's ratio $\upsilon = 0.18$. By using Mat 16 Mode II model, a two-curve model with damage and failure, namely the maximum yield strength curve and the failure model curve, can be defined. The maximum yield strength $\sigma_{\max}$ and the failed strength σ_{failed} are expressed as

$$\sigma_{\max} = a_0 + \frac{p}{a_1 + a_2 p}, \quad \sigma_{\text{failed}} = a_{0\text{f}} + \frac{p}{a_{1\text{f}} + a_2 p} \tag{1}$$

In Eq. (1), a_0, a_1, a_2, $a_{0\text{f}}$ and $a_{1\text{f}}$ are coefficients which can be determined by $a_0=f_c'/4$, $a_1=1/3$, $a_2=1/(3f_c')$, $a_{0\text{f}}=0$ and $a_{1\text{f}}=0.385$, where f_c' is the concrete compressive strength. In the present numerical simulation, the compressive strength of the concrete is set as $f_c' = 45\text{MPa}$. The two curves are shown in Fig. 1(a). The change in yield strength with respect to plastic strain is taken into account. The relationship is given in the form:

$$\lambda = \int_0^{\varepsilon^{\text{p}}} \left(1 + \frac{p}{\sigma_{\text{cut}}}\right)^{-b_1} \mathrm{d}\varepsilon^{\text{p}} \tag{2}$$

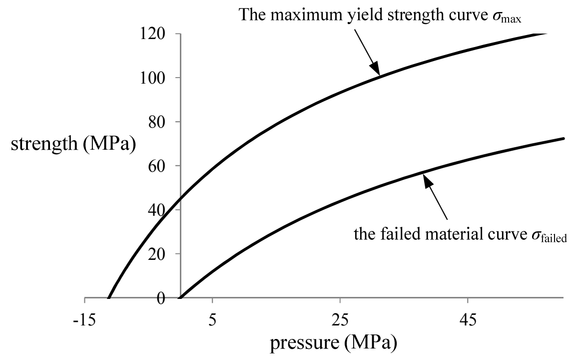
where coefficient b_1 is set as 1.25, p is the pressure, ε_{p} is the plastic strain and σ_{cut} is obtained by the expression:

$$\sigma_{\text{cut}} = 1.7\left(\frac{f_c'^2}{-A_0}\right)^{\frac{1}{3}} \tag{3}$$

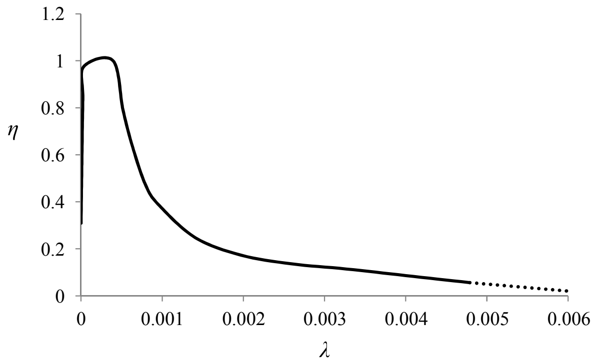
In Eq. (3), A_0 = -145. The yield strength of concrete is given by

$$\sigma_{\text{yield}} = \sigma_{\text{failed}} + \eta\left(\sigma_{\max} - \sigma_{\text{failed}}\right) \tag{4}$$

The relation between η and λ is shown in Fig. 1(b). As the concrete strength is much higher than that of the sand, the EOS is not set for concrete material. A tri-linear polynomial function is automatically generated from the unconfined compressive strength and Poisson' ratio by ANSYS LS-DYNA.



(a) The strength curves for concrete



(b) The relation between scaled yield strength and effective plastic strain

Figure 1. Model for concrete material

The strength equation of the sand is modeled by the Mohr-Coulomb criterion, in which tension strength is set as 0 and cohesion effect is excluded. The Tresca criterion is used as the cut of limit for the shear strength. The shear strength curve for sand can be expressed as

$$\sigma_{\text{ys}} = \frac{\sigma_1 - \sigma_3}{2} = \begin{cases} P\tan 30^\circ & 0 < P < P_{\text{mc}} \\ P_{\text{mc}}\tan 30^\circ & P \geq P_{\text{mc}} \end{cases} \tag{5}$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, P is the pressure and P_{mc} is the Mohr-Coulomb pressure (=0.186GPa), beyond which yield strength is pressure insensitive (Grujicic et al. 2008). Hence, the tension cut-off value (σ_1-σ_3) is 0.258GPa.

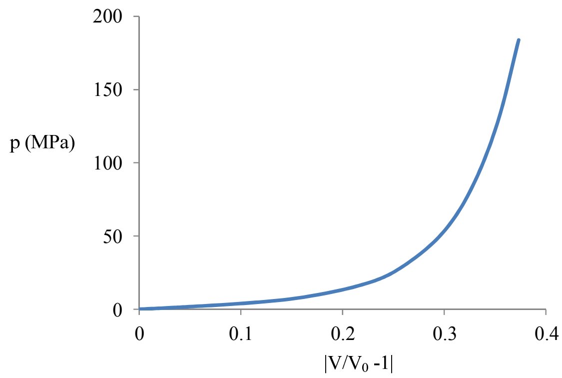
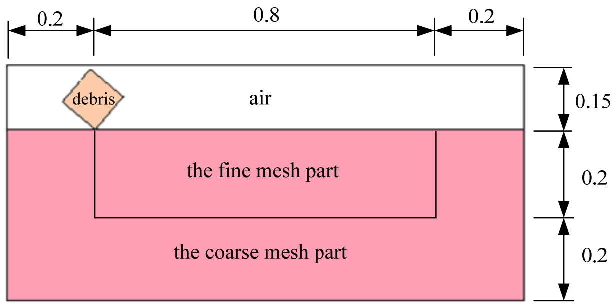
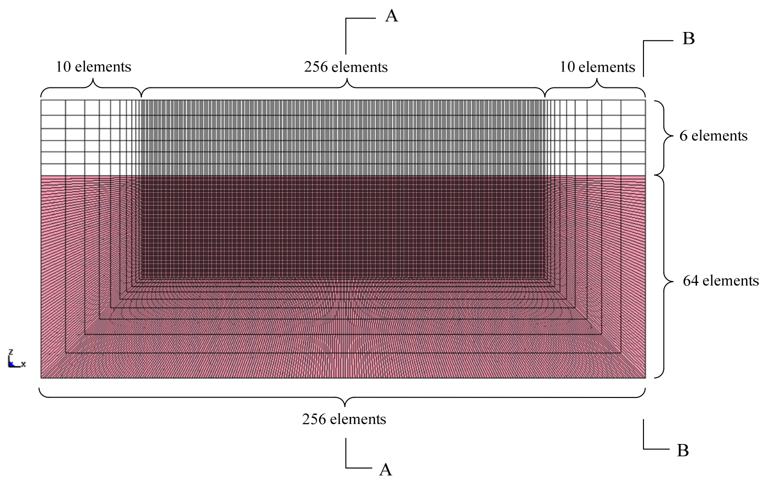


Figure 2. The EOS of sands

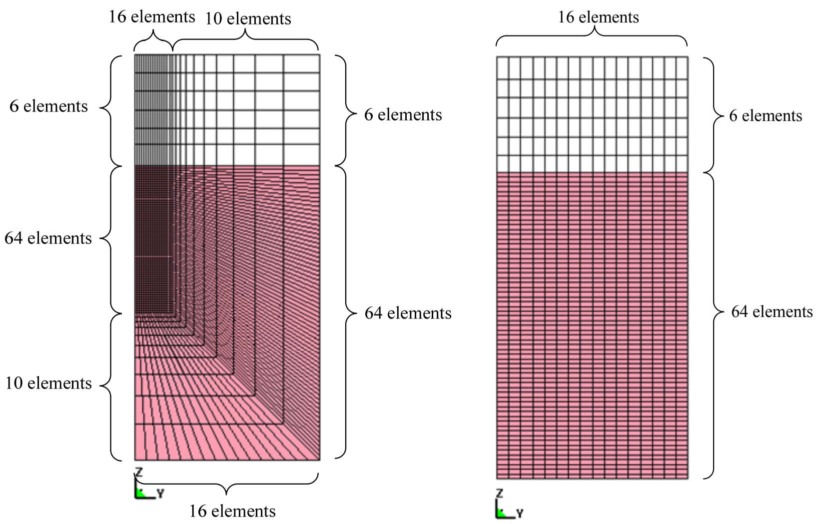
The EOS used for sand is shown in Fig. 2. The initial and the reference densities of sand are both set as 1700kg/m^3. The friction coefficient between the concrete debris and the sands is set as 0.6 (Leonards 1965) in the numerical simulation.



(a) Configuration (X-Z plane)



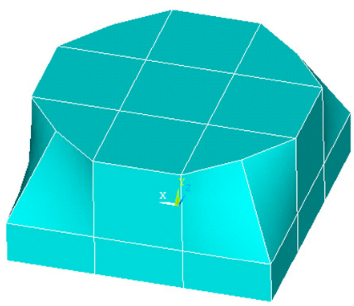
(b) X-Y plane



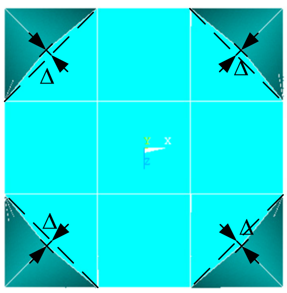
(c) A-A plane **(d) B-B plane**

Figure 3. The Eulerian mesh for the sand and air

For the ALE mesh used, after introducing symmetric condition, only half model is considered as shown in Fig. 3, where the X-Z plane (Y=0) is the symmetric plane. In Fig. 3a, the red part is the impact target (sand) with dimensions of 1.2m (X) × 0.25m (Y) × 0.4m (Z), and the upper part is air with the dimensions of 1.2m (X) × 0.25m (Y) × 0.15m (Z). The meshing scheme of the sand medium and the air is shown in Figs. 3b to 3d. In order to mesh the chamfered cube by hexahedral elements, the half cube is first divided into 3×3×2=18 hexahedrons (Fig. 4a). The four chamfered corners are modeled by collapsed hexahedron. The middle point of the chamfered edge is shifted by Δ=0.0033mm, 0.005mm and 0.0083mm for the 40mm, 60mm and 100mm cube, respectively, as shown in Fig. 4b. Each hexahedron is then further meshed by 3×3×3 hexahedral linear elements.



(a) The half model of the chamfered cube



(b) The shift of the middle point of the chamfered edge

Figure 4: Model of the chamfered cube

The methodology employed for analysis

In each simulation, a set of given vertical and horizontal incident velocities, v_{ix} and v_{iz}, are assigned to all the nodes affiliated to concrete debris so that the debris has ***no*** rotation before it touches the sand surface. At the end of a simulation, the vertical and horizontal rigid body velocities, v_{ox} and v_{oz}, when the concrete debris emerges above the surface level entirely are recorded. The out-going velocity v_o is calculated by $v_o=(v_{ox}^2+v_{oz}^2)^{1/2}$. The out-going angle θ_o is calculated by $\theta_o=\arctan(v_{oz}/v_{ox})$.

The impact outcome parameters, namely the angle change of debris path $\Delta\theta=\theta_i+\theta_o$ and the ratio v_o/v_i are employed in the numerical study to find out the relationship between the impact responses (θ_o and v_o) and the incident conditions (θ_i and v_i). As it is found in (Xu et al. 2013) that the two impact features are almost independent of the impact velocity v_i, only the plot of $\Delta\theta$ against θ_i and v_o/v_i against θ_i are illustrated in this paper.

As shown in the authors' previous work (Xu et al. 2013), a parameter $\varepsilon=(v_o/v_i)^2=5\%$ is adopted to distinguish ricochet. This ricochet criterion is also employed in the present study. It is noted that although the total kinetic energy after impact can be obtained in numerical simulations, only the kinetic energy corresponding to translation is considered.

The numerical results

In this section, the numerical results are presented. The 20mm, 50mm and 80mm □ spherical debris and the 40mm, 60mm and 100mm chamfered cubic debris are employed. It is noted that the numerical modeling was calibrated by comparing the numerical and the experimental results from 50mm ∅ spheres, 60mm and 100mm cubes in (Xu et al. 2013).

The plot of $\Delta\theta$ against θ_i is shown in Fig. 5. It can be found from Fig. 5 that a linear function can be retrieved to evaluate the outgoing angle v_o based on the incident angle v_i as:

$$\theta_o = 0.37\theta_i + 5.5 \tag{6}$$

The plot of v_o/v_i against θ_i is shown in Fig. 6. The scatters in Fig. 6 show a strong linear relationship and the outgoing velocity v_o can be expressed as:

$$v_o = \left(0.8 - 0.018\theta_i\right) v_i \tag{7}$$

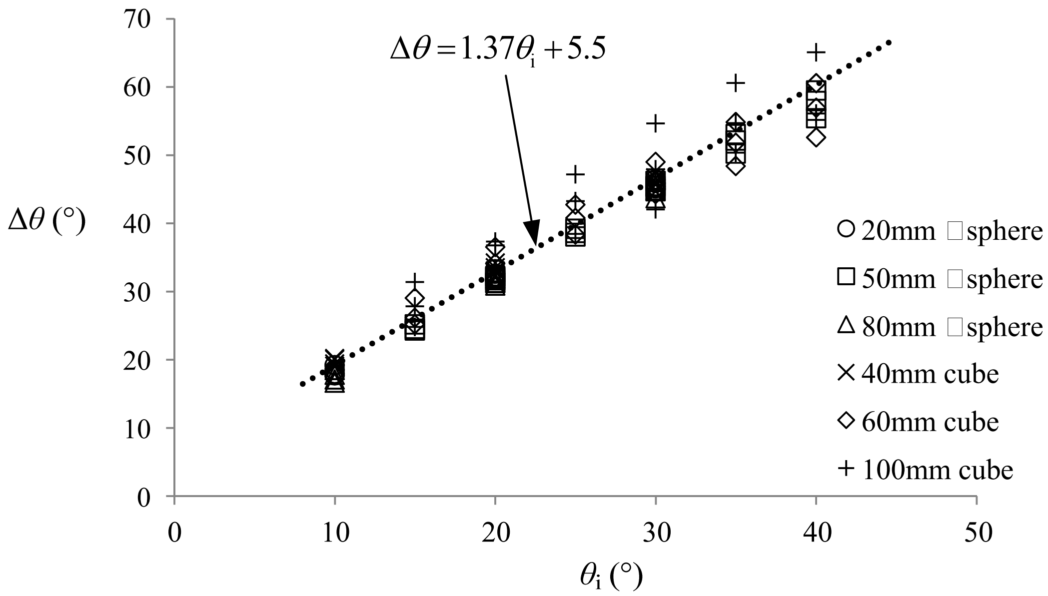


Figure 5. The plot of $\Delta\theta$ against θ_i

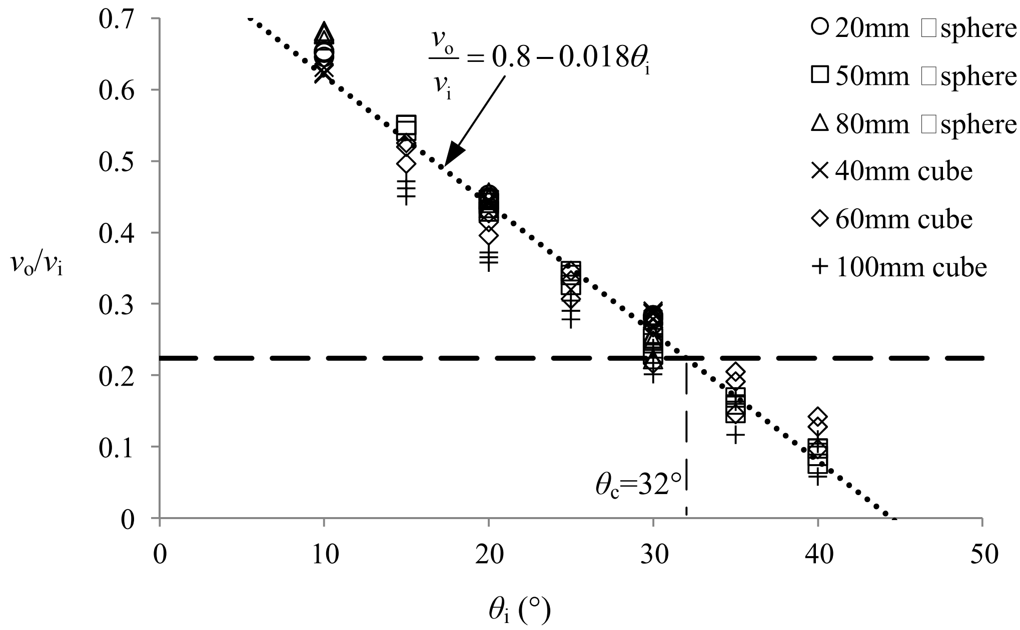


Figure 6. The plot of v_o/v_i against θ_i

Applying $v_o/v_i = 0.224$, which implies ε=5%, into Eq. (7), it can be found that the critical ricochet angle for the concrete debris against sand surface is θ_c=32°.

Conclusions

In this paper, the numerical modeling to simulate concrete debris impacting on sand surface is presented. A total of six types of concrete debris are employed in the numerical simulation. It is found that the concrete debris impact response is independent of the debris size and shape. A unique set of formulations are provided for concrete debris to predict the outgoing angle and the outgoing velocity based on the incident angle and the incident velocity.

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