The effect of moisture content on the explosively driven fragmentation of wet sand

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Abstract. A comprehensive model is established to account for the instability onset of rapidly expanding granular shells subject to the explosion loadings generated by the detonation of the central explosives. The moisture content strongly influences the shock interactions in the wet particle beds and the ensuing evolvement of the granular compacts. A material model for granular materials which can account for the degree of saturation was incorporated into a non-linear dynamic simulation program to investigate the moisture effect on the shock responses of wet granular materials. In conjunction with our instability model, the predicted instability diameters of the expanding dry/wet granular shells are in a good agreement with the experimental results. Particularly the postponed instability onset of the wet granular shell found both experimentally and analytically can largely be attributed to the significantly greater kinetic energy obtained by wet particles thanks to less energy of shock wave consumed in compacting the granular material.

1. Introduction
The formation of post-detonation ‘particle’ jets, evolving from the macro-scale particle fragments, is widely observed in many problems associated with particle dispersal from explosives [1-5]. Specifically, hybrid particle beds reportedly form increased number of jets compared with dry particle bed. The number of jets also increases with the degree of saturation [2-4].

The jetting of dry/hybrid solid particles and the resultant jetting structure closely relate to the dynamic fragmentation of the particle bed since the diameter or equally the thickness of the compacted particle shells at the instability onset proves to be indicative of the subsequent jetting structure [3, 4]. Previous experiments observed a delayed instability onset of wet sand shell which corresponds to the occurrence of a larger number of jets [3]. The jetting instability becomes evident within the first several hundreds of microseconds after the detonation of the central explosive and thus the jet formation is often attributed to the shock interaction in the particle bed and at the charge edge [1-5]. The propagation of the shock wave throughout the particle bed leaves a spall outer layer and a compact accretion inner layer which expands outward driven by the expansion of the detonation gases [4]. Integrating the shock compacted accretion layer into our kinetic energy based instability model [3], and meanwhile coupling the expansion of the particle layers with the expansion of the detonation gases, can give rise to a more realistic prediction of the breakup of granular layers.

The interstitial water plays a significant role in the shock compaction of wet granular materials as well as the yield strength [6]. Since the configuration, the kinetic energy and the viscous flows of the
shock compacted particle layer all contribute to its instability onset [3], it is necessary to take into account the effect of interstitial water. In this paper, we incorporated a granular material model, which can realistically represent the moisture contents, into AUTODYN, a general purpose non-linear dynamics modeling and simulation software, and then carried out the simulations of shock interactions in the dry/wet sand beds. Different configurations of the compacted accretion layers and the isotropic pressure profiles obtained by the numerical calculations were invoked by our instability model, in conjunction with the instability criterion, leading to the prediction of the instability onset.

2. Shock interaction in the dry/wet sand beds

2.1. Material models accounting for the interstitial water of wet sand

![Figure 1](image1.png)

**Figure 1.** Pressure vs. density relation (a) and yield stress vs. pressure relation (b) for sand with different degree of saturation.

We employed a modified porous/granular material model of Laine and Sandvik [7] developed by Grujicic et al. [6] which can account for the effect of degree of sand saturation (referred to as the CU-ARL sand model hereafter). For details of the CU-ARL model, readers can be referred to [6]. The compressibility of wet sand is increasingly reduced with increasing moisture contents due to the water being trapped inside the pores under the very high deformation rate [see figure 1(a)]. Meanwhile the inter-particle water-induced lubrication effect gives rise to a considerable reduced strength of wet sand before the pressure reaches the Mohr-Coulomb pressure ($P_{MC} = 1.864 \times 10^5$ kPa) beyond which the yield stress is pressure insensitive, as shown in figure 1(b). The cohesive strength of wet sand, $P_{fail,sat}$, is expected to increase with the saturation ratio $\beta$:

$$P_{fail,unsat} = \beta^4 P_{fail,sat}$$

where $P_{fail,sat}$ (set equal to 729 kPa) is the failure pressure in saturated sand.

2.2. Shock interaction in the wet sand layers

The CU-ARL sand model is incorporated into AUTODYN to analyse the problem identical to the one investigated experimentally in [3]. Figure 2 shows the geometry of the model, which consists of a dry/wet sand shell with an inner radius of 20 mm and an outer radius of 65 mm surrounding a spherical TNT explosive (20 mm in diameter) described by the Jones-Wilkins-Lee state equation.

![Figure 2](image2.png)

**Figure 2.** Computational model of the present work. Three sets of the transducers are placed along the radii oriented at three different angles to the horizontal: $0^\circ$, $90^\circ$, and $135^\circ$. 
Figure 3. variations in density profiles of dry (a) and wet (b) sand subject to the shock loadings caused by the central detonation in the geometry of figure 1.

Figure 3 shows the evolvement of the density profiles in the dry (a) and saturated (b) sand shells as a result of the shock interaction following the TNT denotation. Both dry and wet sand undergo a sequence of resembling events, namely the initial densification caused by the outward-going shock wave, the following dilation induced by the reflected rarefaction wave, the recompression driven by the expanding detonation products. The early release wave leaves an outer thin spall layer and an inner thicker accretion layer. This inner layer initially accelerates due to the outward impulse of detonation products and thickens as it gathers up the loosened sand. But then it will behave as an incompressible material and expand outwardly mainly dominated by its inertia gained in the early stage.

Because of lower compressibility, the volume of the shock compacted wet sand is about 94.8% of the initial volume, much higher than the dry sand whose volume is compressed to about 63.1% of the initial one. The accretion layer gains its kinetic energy from the expansion of detonation products as well as the shock interaction. Due to the major part of shock energy being consumed in sand compaction and already extensive expansion of detonation products before the accretion layer of dry sand sets to take shape, the accretion layer of dry sand expands outwardly at much lower speed than that of wet sand as shown in figure 4. The isotropic pressure in the accretion layer implies the effect of moisture content in accordance with that on the expanding velocity (see figure 5), where dry sand is subjected to lower pressure as a result of less work of detonation products expansion contributing to driving the accretion layer.

Figure 4. Temporal variations in the velocities of the inner edges of the accretion layers of dry and wet sand.
3. Instability onset of the expanding dry/wet sand shells

To address the instability of the expanding granular shells, we proposed a kinetic energy based instability model which involves the competition between the stabilizing inertial forces and the destabilizing viscous flows. Figure 6 shows the geometry of this model, details of which can be found in [3]. The basic assumption of this model is the incompressibility of the sand shell, which only holds for the accretion layer after its initial thickening as discussed in section 2.2. Equation (2) gives the expression of the circumferential tension as a function of the shell expanding

\[
T = \frac{\rho V^2 R}{2} \left( \frac{1}{3} - \frac{4R_1^3}{3R_2^2} + \frac{R_1^4}{R_2^3} \right) + \eta V \sqrt{2 \left( \frac{1}{4} + \frac{3R_1^2}{4R_2^2} - \frac{R_1^3}{R_2^3} \right)}
\]

\[
-2\rho \left( V^2 R_1 + AR_1^2 \right) \left( \ln \frac{R_1}{R_2} - 1 + \frac{R_1}{R_2} \right) + \sqrt{3\pi} R_1 \left( 1 - \frac{R_1}{R_2} - 2 \ln \frac{R_1}{R_2} \right)
\]

where \( \rho, R_1, R_2, V_1 \) and \( A \) are the compact density, the instantaneous inner radius, the outer radius, the velocity and the acceleration of the inner edge of the accretion layer, respectively. \( \eta \) is the effective viscosity. For dry sand \( \eta \) can be estimated by equation (3)[8]

\[
\eta_{dry} = \frac{2\mu (I) P}{\sqrt{2d_{grain}}} \quad \mu (I) = \mu_i + \frac{\mu_0 - \mu_i}{I_0/I + 1} \quad I = \frac{\mathcal{F}d_{grain}}{\sqrt{P/\rho_p}}
\]

where \( I \) is the inertial number, \( P \) is isotropic pressure, and \( \mathcal{F} \) is the shear rate. For wet sand [9]

\[
\eta_{sat} = B(\xi) \sqrt{m_{grain} \xi} \quad \xi = \frac{N^c}{Pd_{grain}}
\]

where \( N^c \) denotes the cohesive force between particles (of the order of 0.05 N/m), \( B(\xi) \) is close to 1 for the small value of \( \eta \). For the cases studied here, \( \eta_{dry} \) and \( \eta_{sat} \) are both on the order of \( 10^{-3} \), which leads to ignorable term involving \( \eta \) compared with other terms in (2).
Taking into account the instantaneous configuration of the accretion layer and the evolving isotropic pressure (see figure 5), we can plot the tension $T$ varying with the expanding accretion layer as shown in figure 7. For the dry sand, the accretion layer undergoes a transition from compression to tension and the instability would initiate upon this transition due to the lack of ability of supporting tensile loading in dry sand. The cohesive forces between wet sand grains allow wet sand to sustain a moderate tension. The instability onset of wet sand instead takes place at the point of maximum tension rather than the transition from compression to tension. Figure 8 compares the experimentally observed breakup radii of sand shells with a variety of saturation and the theoretically predicted instability onsets of dry and wet sand, which gives rise to a good agreement.

4. Conclusion
The instability onset of the expanding granular shell is substantially controlled by its expanding velocity which is indicative of the stabilizing inertial forces. Due to the weak compressibility, the work produced by the expansion of the detonation products mainly contributes to the acceleration of the accretion layer of the wet sand as opposed to being consumed by the compaction of the dry sand. The wet sand thus gains greater expanding speed than the dry sand. Stronger inertial forces are the key driving forces underlying the delay of the fragmentation of the wet sand.

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