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On the study of ricochet and penetration in sand, water and gelatin by spheres, 7.62 mm APM2, and 25 mm projectiles

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Abstract

We examine the ricochet and penetration behavior in sand, water and gelatin by steel spheres, 7.62 mm APM2 and 25 mm projectiles. A threshold impact angle (critical angle) exists beyond which ricochet cannot occur. The Autodyn simulation code with the smooth particle hydrodynamic (SPH) method and Impetus Afea Solver with the corpuscular model are used and the results are compared with experimental and analytical results. The resistance force in sand for spheres was proportional to a term quadratic in velocity plus a term linear in velocity. The drag coefficient for the quadratic term was 0.65. The Autodyn and Impetus Afea codes simulate too large penetration due to the lack of a linear velocity resistance force. Critical ricochet angles were consistent with analytical results in the literature. In ballistic gelatin at velocities of 50–850 m/s a drag coefficient of 0.30 fits the high speed camera recordings if a linear velocity resistance term is included. However, only a quadratic velocity resistance force with drag coefficient that varies with the Reynolds number also fits the measurements. The simulation of a sphere in water with Autodyn showed too large drag coefficient. The 7.62 mm APM2 core simulations in sand fit reasonable well for both codes. The 25 mm projectile ricochet simulations in sand show consistency with the high speed camera recordings. Computer time was reduced by one to two orders of magnitudes when applying the Impetus Afea Solver compared to Autodyn code due to the use of the graphics processing units (GPU).

Keywords: Ricochet; Simulation; Sand; Gelatin; Autodyn; Impetus Afea Solver; Smooth particle; Sphere

1. Introduction

Ricochet occurs when the final velocity vector of the center of mass of a projectile is oriented away from the target and is associated with small impact angles or high obliquity (obliquity is defined as the angle between the normal surface vector and the velocity vector of the center of mass of the projectile). The ricochet angle and the ricochet velocity are dependent on the impact velocity, obliquity angle, yaw, mass of the projectile, geometry, moment of inertia and target properties. A threshold impact angle (critical angle) exists beyond which ricochet cannot occur. However, the relationship between critical impact angle, projectile nose shape, amount of water, mineralogy and impact velocity is still not fully understood [1].

1.1. Sand

Sand grain failure in front of the projectile may be an important energy dissipation mechanism in sand. Very fine white powder is observed in the wake of the projectile due to the pulverization in front of the projectile. It has been estimated that 8% of the energy of the projectile was consumed in pulverization of the individual sand particles in hypersonic sand penetration experiments [2]. The yield point during compressing of aggregate sand can be correlated to the initiation of particle failure [3]. When sand is under loading it undergoes a change in shape and compressibility. The volume decreases due to changes in grain arrangements where microscopic interlocking with frictional forces between interacting particles lead to bending of flat grains and rolling of rounded particles. If the load is further increased, the grains eventually become crushed. High pressure compression tests have revealed different types of damage mechanisms, (a) single abrasion fracture, (b) multiple abrasion fractures, (c) major splitting of particles into two or more particles, (d) breakage of sub particles,

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(e) pulverization of particles into many small pieces. However, under high rate compressive loading, the only mode of failure observed was pulverization, Parab et al. [4]. At very low velocities frictional resistance exceeds hydrodynamic resistance. At projectile velocities above the speed of sound in the sand, particles may lock up instead of flowing locally. However, lock up of particles may depend on the density. The difference in response for high and low velocity is related to the timescale required for relaxation of force chain structures. A comprehensive review of the response of granular media to rapid penetration was recently published by Omidvar et al. [5].

1.2. Modeling

Modeling by discrete element methods may require extensive material parameters at high strain rates, large strain, and high pressure. Use of simple analytical models is thus for some cases a viable alternative. When the deformation of the projectile is negligible the rigid body assumption can be applied. For linear projectile trajectories Robins [6] and Euler [7] assumed that for sand the force was a constant. Poncelet [8] set the force equal to a constant plus a term proportional to the square of the velocity. Resal [9] set the force proportional to the velocity plus a term proportional to the square of the velocity. Forrestal and Luk [10] applied a force that was a constant plus a term proportional to the square of the velocity based on the cavity expansion theory. Agreement within 19% was shown when comparing with experimental results. Allen et al. [11] developed a model where an abrupt transition in drag force occurs at the critical velocity, of about 100 m/s, believed to be due to transition from inelastic to quasi-elastic impacts. Projectiles with nose cone angles from 180 to 90° were stable. For penetration problems with relative large obliquity, yaw or pitch, nonlinear motion is expected and the projectile may even reverse its motion toward the target surface (ricochet). However, even for very small yaw, or obliquity, instability may occur and the trajectory becomes curved. Soliman et al. [12] studied many years ago spherical projectile ricochet in water and sand theoretically and experimentally. For water and sand it was found that the ricochet angle was around 20% larger than the impact angle. Bernard et al. [13] show that the trajectory went from linear to curved when the impact velocity was increased from 427 to 512 m/s for 3.7° obliquity. Above 30° obliquity the trajectory was curved and the projectile might move towards the target surface when the projectile's slenderness ratio L/D (length to the diameter of the projectile) was reduced. Projectiles with nose cone angles less than 90° become progressively more unstable with decreasing cone angle. For sand it was found that the critical angle decreases with increasing velocity but a cut-off angle was found.

Daneshi and Johnson [14,15], studied ricochet of spherical and dumb-bell shaped projectiles in sand and found that the volume of sand displaced from the crater was proportional to the initial momentum of the projectile. Bai and Johnson [16] examined the effect of projectile speed and medium resistance on ricochet in sand. Johnson et al. [17] examined the effect of high velocity oblique impact and ricochet of mainly long rod projectiles. Savvatteev et al. [18] examined high-speed (up to 4000 m/s) penetration into sand. Full melting of the steel bullets occurs at the velocity of 1800–2000 m/s. Anderson et al. [19] studied the flow field center migration during vertical and oblique impacts. Reducing the friction between grains and projectile increases stability [20]. Bless et al. [21] found that a hemi spherical nose gave less resistance and that projectiles were stabilized by fins. Nishida et al. [22] examined the effect of sand density and projectile diameter on critical incident angles of projectiles impacting granular media. The critical reverse velocity is the velocity where the projectile starts to move back to the surface of the target. Li and Flores-Johnson [23] investigated the trajectory in soil penetration by implementing a resistance function based on the cavity expansion theory into ABAQUS code. It was found that the critical reverse velocity decreases with increasing obliquity and that tumbling of the projectile increases with the ratio L_c/L, where L_c is the distance from the nose of the projectile to the center of mass and L is the length. Ye et al. [24] studied the influence of projectile rotation on the oblique penetration in granular media. See Johnson et al. [17] for a review of high velocity oblique and impact ricochet.

Impacts on gelatin show significantly different displacement fields compared to sand [25]. See also Wen et al. [26] for impact of steel spheres in gelatin at moderate velocities.

Rigorous hydrocode calculations can offer insight into the physics of ricochet. Numerical models have increasingly been used in analysis of projectile penetration into soils and granular materials due to the inherent complexity of the problem. Soil or sand can be considered as a three phase medium consisting mainly of solid grains, with portions of water and air. Moxnes et al. [27] proposed a continuum MO-granular model where parameters are constructed by using a quasi-static unilateral compression test, and validated by using a high-speed piston (up to 300 m/s) impacting a granular pyrotechnic bed. The piston and the tube were made of lexan, which made it possible to record the piston position and the compaction wave propagating in front, by using a high-speed camera. The experimental recordings were compared to numerical simulations, using the explicit numerical code Autodyn-2D, and a new constitutive material model for the porous material. The models apply a hydrostatic compaction curve as a function of the density, a model for the yield stress as a function of pressure and elastic modulus as a function of density. The model does not include any strain rate dependency of yield stress. This is an assumption that may be good as long as the strain rate is above 10^3/s [28]. For a review of stress–strain behavior of sand at high strain rates, see Omidvar et al. [29]. Laine and Sandvik [30] derived quasi static tri-axial material parameters for dry sand using the MO-granular continuum model implemented in Autodyn. The model applies when soil packing density is sufficient high and hence the particle–particle contacts are semi-permanent. We agree with Grujicic et al. [31] that this is the widely used soil model in military communities and it has been widely used for shock simulation involving dry sand within the Autodyn community with quite decent results, e.g. for determining blast load from buried mines [32,33]. However, the model also has been used in civil applications such as road side safety [34]. The