Velocity Regimes for Sphere Penetration of Granular Materials

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Experiments were conducted to measure deceleration during penetration of granular materials.

There were two materials: ground fused quartz or silica sand. Three types of saturation: dry, oil (for quartz) and water (for sand). For most materials, there were two different relative densities.

Projectiles were either spheres (10 or 12 mm) or hemispherical-nose rods (10 mm).

Velocities were up to 300 m/s, achieved with compressed gas guns.
A PDV was used to measure $V(t)$

- This is a doppler device, based on heterodyning with a laser source. Its features include a very large DoF and dynamic range.
- Spherical projectiles, 14 mm.
- Projectiles could be observed through cavity
- From $V(t)$ integrate to get $V(x)$ or differentiate to get $dV/dt$. 

Measurements of $V(t)$
DOP experiments measured $p(V)$.

- Spherical projectiles: made from Al, steel, or WC.
- Penetration measured by recovery.
- Data: penetration ($x$) vs $V$.
- Estimate: $\Delta V/\Delta t \approx <V> (\Delta V/\Delta x)$.

Measurements of $x(V)$

Phenomenology shown by DOP experiment conducted near a window.
High speed camera used to measure $x(t)$ during penetration.

- Hemispherical or conical nosed rod the a sting on the back.
- $X(t)$ data double differentiated to give $dV/dt$. 

Measurements of $x(t)$
The PDV results can be used to directly compare penetration resistance of different materials.

- Steeper curves mean greater penetration resistance.
- Resistance increases with density.
- Resistance decreases with saturation.
- Resistance is higher for sand than for quartz.
- For saturated materials, signal was lost at about 50 m/s.
For sand there are apparently three velocity regimes.

- Deceleration is very high during embedment and shock formation.
- Deceleration inversely proportional to $V$ for $V > V_c \approx 100 \text{ m/s}$.
- Below $V_c$ deceleration proportionality increases, but then becomes nearly constant.

Acceleration for loose dry sand.
For each experiment, penetration resistance is computed.

- Force on projectile, $F = \frac{M}{dt}$
- Average penetration resistance over hemisphere $= \frac{F}{A}$
- This is also the stress that the projectile exerts on the sand.
- Max values are 70 – 110 MPa.
An practical implication of these results is that for sand penetration, there is little advantage to shooting >100 m/s.

- This is borne out by various studies of penetration of spheres and rods as a function of velocity.
- The reason is that the force resisting penetration increases approx as $V^2$.
- Most penetration takes place at low velocity.
Based on $\frac{MdV}{dt} = \frac{1}{2} \rho CAV^2$.
Variability shows deviation from simple inertial resistance.
Thus the usual assumption that at high velocities resistance is due to inertia or dynamic friction is not correct.
The “drag coefficient” has local maximum at $V_0$. 

Loose and dense sand penetrated by spheres.
For sand penetrated by a conical nose rod:

High C at low velocities arises because deceleration becomes nearly constant, meaning resistance is due to friction, not inertia (and $C \approx 1/V^2$).
This is the velocity beyond which there is large scale comminution of the sand.

Kovtov hypothesis: for $V > V_c$, sand becomes stronger as pores are crushed out. It becomes possible to form a false nose that makes penetration easier.
Depends on material
  Sand is harder than quartz.
  Dry materials are harder than wet materials.
  Resistance increases with density. *
Depends on velocity wrt a critical value
  Critical velocity has highest drag coefficient.
Behavior for $V>V_c$
  Resistance increases almost as $V^2$, e.g. inefficient penetration.
Behavior for $V<V_c$
  $C$ increases with velocity.
Behavior as $V$ goes to zero.
  Resistance becomes frictional.