FOOTPRINTS: THE ROLE OF PARTICLE CHARACTERISTICS

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Soils are particulate materials. *Grain size* determines the balance between particle-level forces (skeletal, weight, van der Walls attraction, double layer repulsion, capillary and viscous drag - Figure 1). *Grain size distribution* establishes the range of possible particle packing configurations. And, *particle shape* (i.e., sphericity, angularity and roughness) defines particle interactions, such as slippage vs. rotation, and the development of both inherent and stress-induced anisotropy (see Figure 2). Therefore, macro-scale behavior is determined by particle-level characteristics. In particular, extreme void ratios e_{max} and e_{min} and critical state soil parameters (ϕ_{cs} Γ and e_{cs}) can be estimated from roundness R, sphericity S (for $C_u \leq 2.5$ - Cho et al., 2004):

$$\phi_{cs} \approx 42^o - 17^o R$$
$$\Gamma \approx 1.2 - 0.4R$$
$$e_{cs} \approx 1.1 - 0.21(R + S) \qquad \text{at } p' = 100kPa$$
$$e_{max} = 1.5 - 0.41(R + S)$$
$$e_{min} = 0.9 - 0.22(R + S)$$

The state of stress determines the stiffness and strength of granular materials, as predicted by the Hertzian contact theory and Coulomb's failure criterion. Near-surface soils are subjected to very low initial effective confining stress and the stress induced during load application typically far exceeds the initial effective stress. Therefore, the stiffness and strength of granular materials evolves during loading. This situation enhances the non-linear nature of soil behavior and is responsible for the characteristic "footprint" signature left behind after load removal.

The load-deformation of a circular rigid footing R=0.25m is numerically simulated using the modified cam clay material model, using material parameters experimentally determined in the laboratory (ABAQUS – axi-symmetric). The two cases shown in Figure 3 correspond to an angular well-graded sand (blasting sand) and a quasi-spherical poorly-graded sand (glass beads). The importance of particle shape on footprint development is highlighted.

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The initial effective stress increases with depth according to the local gravity. Gravity on the Earth (a_{moon}=9.81 m/s^2) is almost three times grater than on Mars (a_{mars}=3.73 m/s^2), and about 6 times greater than on the Moon (a_{moon}=1.62 m/s^2). Therefore, the initial effective stresses at a given depth are proportionally higher on the earth. Figure 4 shows the force-deformation response experienced by the circular rigid footing on the surface of the Earth, Mars and the Moon (R=0.25m – same blasting sand). The applied force in each case is normalized by the local gravity and it can be interpreted as the mass placed on the footing. The similarity between predicted normalized force-deformation responses is a consequence of the dependency of strain on the normalized deviatoric stress σ'_d/σ'_o in granular materials (where σ'_o is the initial effective stress).

Finally, footprint details (such as steep edges observed in astronauts' footprints on the moon) can be explained by a combination of particle shape effects coupled with particle weight-to-attraction force ratio (refer to Figures 1 and 2).

Reference:

Cho, G.C., Dodds, J. and Santamarina, J.C. (2004), "Particle shape effect on packing density, stiffness and strength – Natural and crushed sands" (ASCE   Geotech. J. – conditionally accepted).
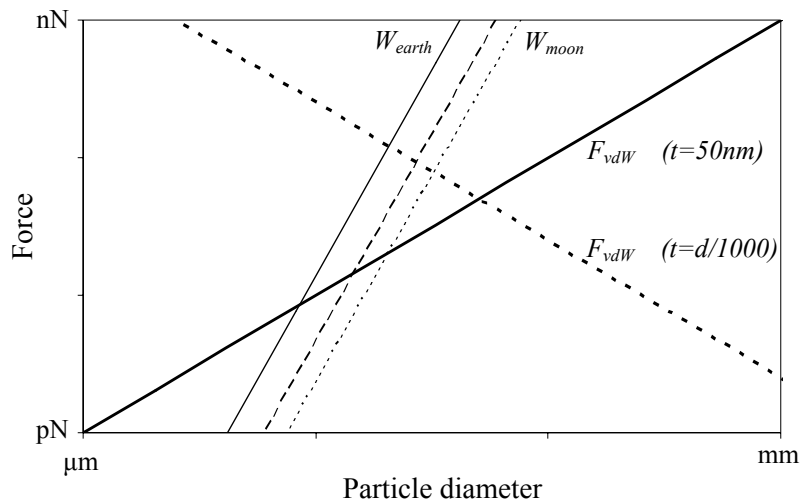
Figure 1.   Particle-level Forces and particle size: Particle weight and van der Waals attraction (spheres; assumed Hamaker constant for mineral-vacuum-mineral A=6·10^{-20} J).
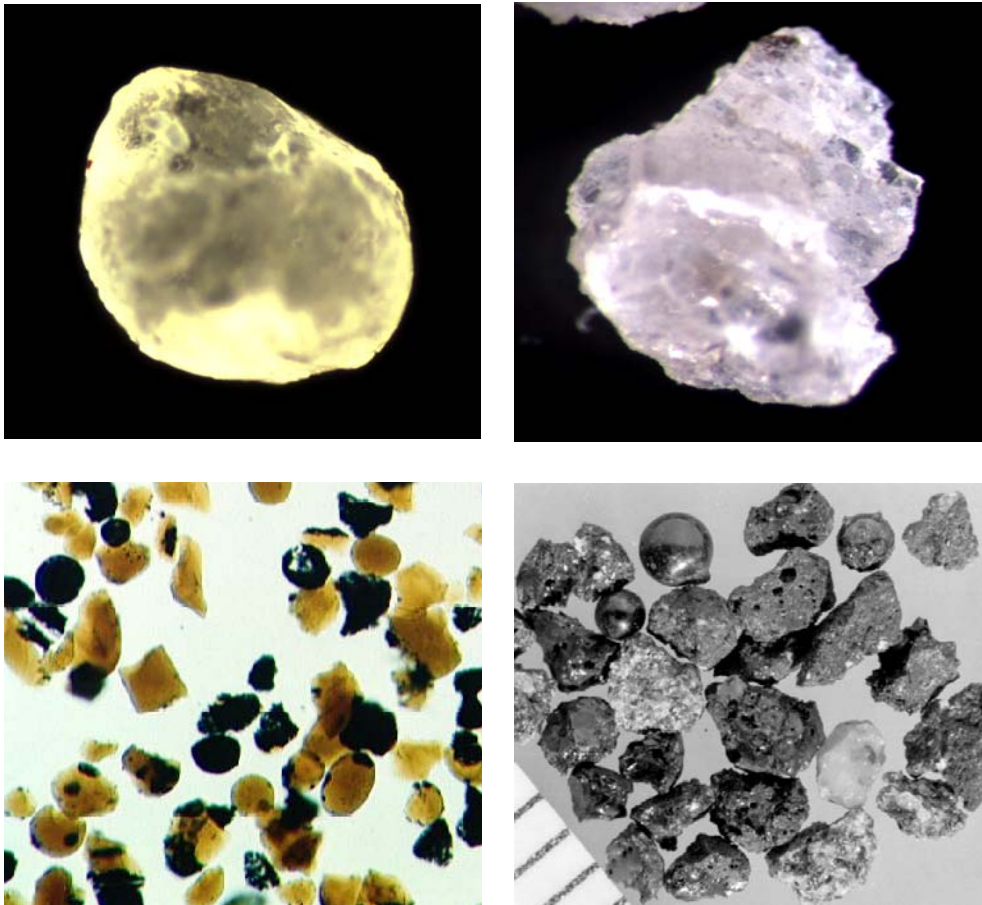
Figure 2. Shape of grains: (a) Ottawa sand d=0.35 mm, (b) crushed granitic sand d=0.35 mm, (c) Moon dust d=20~45μm, Apolo 17, NASA-JSC, (d) Moon sand d=1~3mm, NASM-Smithsonian.
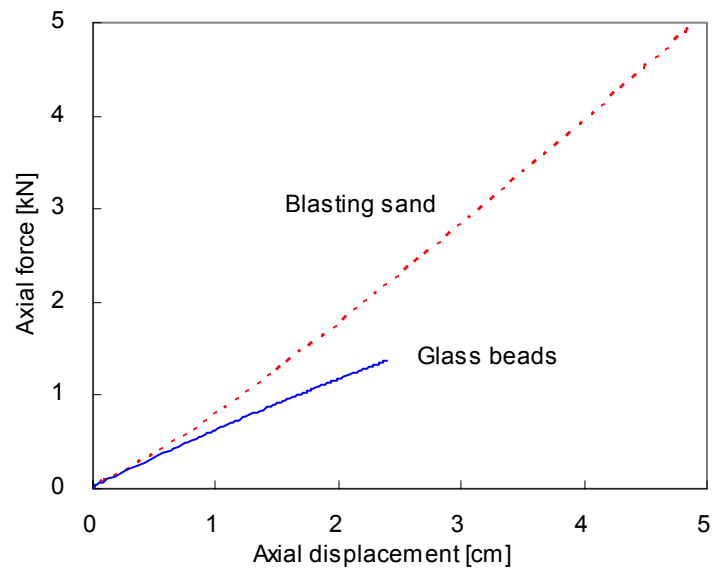
Figure 3. Load-deformation on two different soils with different grain shape – Footing on the surface of the Earth
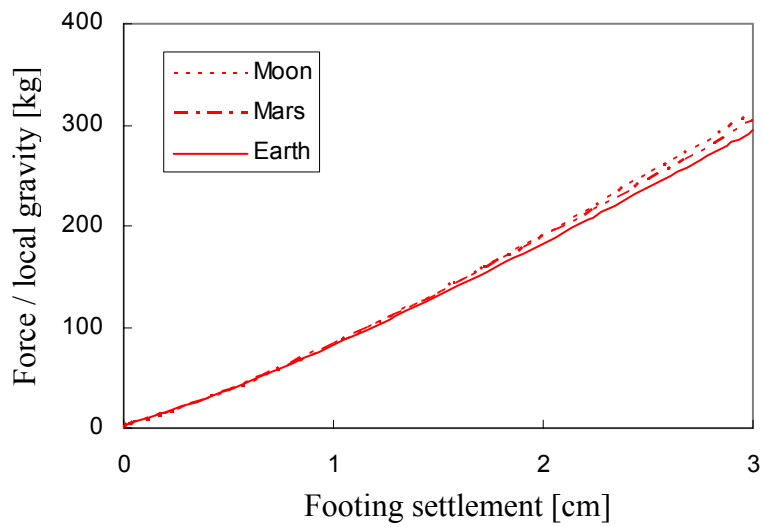
Figure 4. Normalized force vs. deformation – Different gravity conditions (blasting sand)