Friction in Soils: Micro and Macroscale Observations

La Fricción en los Suelos: Observaciones a Micro y Macro Escala

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Abstract

The development of friction in minerals and soils has advanced in stages. Unprecedented experimental and numerical tools available today allow the study of friction in minerals at the atomic scale and in soils at the particle level. Results from these investigations render new insight that can be used to explain macroscale observations in soils (e.g., friction anisotropy and the correlation with plasticity) and to explore anomalous soil responses. Furthermore, this enhanced understanding can lead to the development of "engineered soils" where friction is a design parameter.

Resumen

La evolución del concepto de la fricción en minerales y suelos ha avanzado en etapas. Las herramientas experimentales y numéricas disponibles actualmente permiten estudiar la fricción en minerales a escala atómica y en suelos a nivel de partículas. Los resultados de estas investigaciones generan nuevas ideas que se pueden usar para explicar las observaciones en la macroescala de los suelos (ej. fricción anisotrópica y la correlación con la plasticidad), así como para explorar la respuesta anómala de algunos suelos. Además, el entendimiento realzado puede conducir a desarrollos de "suelos diseñados" donde la fricción es un parámetro de diseño.

1 INTRODUCTION

The shear strength in uncemented particulate materials and jointed rock masses is controlled by friction. Frictional strength refers to the shear strength that is proportional to the normal stress and independent of velocity (first order). Coulomb, summarizes in his assay the understanding of friction by the end of the XVIII century (Coulomb, 1776): *"Friction and cohesion are not active forces like gravity, which always exerts its full effect, but only passive forces; these forces can be measured by the limits of their strength…strength due to friction is proportional to compressive force, as was found by Amontons…Cohesion is measured by the resistance that solid bodies offer to the simple separation of their parts. …Cohesion is assumed to be zero… for newly-turned soils"*

The purpose of this manuscript is to present recent information relevant to the understanding of soils' frictional behavior. The manuscript starts with a brief review of the history of friction to highlight the salient stages in the development of concepts and ideas as they affect current and future developments in geotechnical engineering. Then, micro-scale phenomena are identified. The rest of the manuscript addresses friction in particulate materials, identifying general trends and anomalous behavior, and promising future developments

2 BRIEF HISTORY OF FRICTION

The main stages in the development of friction are identified next.

Stage 1: Reducing friction by trial and error. This period starts with innovations such as the wheel and rollers used in Mesopotamia before 3500 BC. Egyptians understood by 2750 BC, the difference between friction generated when sliding rock on sand and rock on wet silt.

Stage 2: Early Theoretical Developments. Two crucial observations are found in Leonardo da Vinci's manuscripts [1452-1519 – Italy]. First, friction is independent of the apparent area of contact, and second, friction doubles when the applied normal load doubles. Guillaume Amontons [1663-1705 – France] re-discovered da Vinci's frictional laws, and presumed that friction was due to roughness and the overriding of asperities. John Theophilus Desaguliers [1638-1744 – England] observed the "mechanical paradox" that more polished surfaces exhibit higher friction, studied the interaction of lead balls, and hinted on the role of adhesion on friction. Later, Charles August Coulomb [1736-1806 – France] referred to Amontons observations, as noted in the quote above, and emphasized the intuitive idea of surface roughness. However, when a body displaces relative to another one along a horizontal surface, it is climbing some asperities and falling off others, therefore, there is no energy dissipation. This observation led John Leslie [1766-1832 – England] to question the asperity theory.

Stage 3. Lubrication and Adhesion. Developments in hydrodynamics promoted experimental studies in hydrodynamic lubrication starting in the XIX century, showing that the friction coefficient becomes a function of the sliding velocity and if the sliding velocity becomes sufficient small, the lubricant is displaced, the two bodies experience solid-solid contact and the friction coefficient increases drastically (Figure 1). This is not the case if the lubricant binds onto the surface, giving rise to boundary lubrication, as shown by W. Hardy and I. Doubleday [1922 – England]. By 1950, Philip Bowden [1945-1968 – Tasmanian] and David Tabor [1968-1981 – Australian] had completed a series of friction studies at Cambridge University and postulated the adhesion theory of friction to demonstrate daVinci–Amontons laws, where friction is proportional to the true contact area, rather than the apparent area (Bowden and Tabor, 1982 – also evident in Terzaghi's early work).

Stage 4. Fundamental Microscale Understanding. The development in computers allowed for the first molecular dynamics simulations in the 1950's [for example, Alder and Wainwright in 1956 – Laurence Livermore NL]. The vast increase in computer power that followed made possible realistic molecular dynamic simulations of a sliding stylus/asperity including the role of adsorbed layers in the 1990's. In the meantime, the development of the atomic force microscope by G. Binnig, C.F. Quate, and Ch. Gerber [1986 – Switzerland] opened important alternatives to the experimental study of friction at the microscale. In particulate materials, microscale experimentation [such as the work by Oda starting in the 1970's – Japan] and numerical simulations [P. Cundall, 1970's – USA] led to a major understanding of the nature of friction in soils.

Efforts on the fundamental understanding of friction continue today, addressing both minerals and the frictional strength in soils. Furthermore, current developments point to a new series of applications of this enhanced understanding, ranging from micro-mechanical devices to "engineered granular minerals".

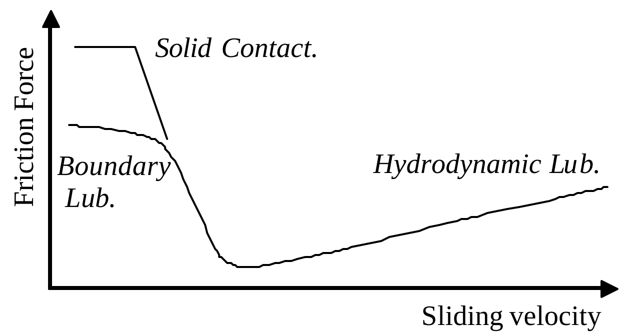

Figure 1 The effect of fluids on friction

3 MICROSCALE MECHANISMS

Several microscale energy loss mechanisms can be identified when two interacting mineral surfaces are subjected to shear: wear, plastic deformation, adhesion, and multiple interfacial mechanisms that convert mechanical energy into some other form of energy that dissipates (e.g., heat, emission of elastic waves, emission of electromagnetic waves).

Prominent findings from recent atomic-scale studies of friction between mineral surfaces (molecular dynamics and AFM) and particle-scale studies of shear strength in soils (experimental and discrete elements) are summarized next; a comprehensive list of references is available from the authors.

3.1 Contact-level Processes- Atomic Scale

Shear force. ranges between 10^{-2}N/m^2 and 10^{10}N/m^2 (Krim, 1996). Strong chemical bonds (chemisorbed) render shear force 3 orders of magnitude higher than weak bonds (physisorbed).

True area of contact. $A_{true}=N/\sigma_y$ where N is the normal force and σ_y the yield strength of the material.

Stick-slip. It is observed in boundary lubrication, for fluid layers thinner than ~10 Å. Molecular dynamics show periodic freeze/flow cycles during shear (Persson, 1998 and references therein).

Friction and Noise. Friction causes noise and noise alters friction (implications are discussed in Wang and Santamarina 2003).

Commensurate surfaces. Surfaces lock if they share a common periodicity. Amontons-type response develops between incommensurate surfaces with adsorbed layers.

Asperity at the atomic scale. All surfaces are electrically rough (surface charges). The effect of roughness is extended away from the surface by rotational restrictions in polar water molecules. Friction is negligible when the two surfaces are separated at a distance greater than about ~10 Å.

Contact level forces. Repulsion (Born and osmotic) must balance the combined effects of: skeletal forces due to effective stress, capillary forces, and electrical attraction (van der Waals, and Coulomb).

Note that the "effective normal force" at interacting asperities is a combination of skeletally transmitted forces and contact-level capillary and electrical forces (attraction and repulsion). Therefore, the acting normal resultant force at the contact may differ from the value imposed by the applied effective stress. van der Waals attraction and capillarity are relevant in soils with fines.

3.2 Particle-level Processes

Internal anisotropy. Friction reflects the maximum internal anisotropy in contacts and forces a soil may take before particle chains buckle.

Rotational frustration. The higher the number of interparticle contacts (higher soil density) and the higher the particle surface roughness and angularity, the more difficult particle rotation becomes (consider toothed gears - this mechanism underlies the intuitive concept of "interlocking").

Competing effects. To overcome rotational frustration, the void ratio must increase to reduce interparticle coordination. But, load carrying particle columns buckle, the void ratio decreases, and the coordination number increases.

Particle alignment takes place in particles with length ratio >~1.1 and lowers residual friction angle at large strains.

Development of strong bonding between particles. It is pH and ion concentration dependent, it is promoted in multiple-mineral soils (different pH-dissolution responses), and it is more readily attained when multi-valance ions are present, e.g., Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+} (Santamarina et al. 2001).

Aggregations. Conglomerates of fine-grained particles may act as coarse particles, so that the behavior of fine grained soils resembles the behavior of coarse grained media. Lightly cemented soils shear into blocky structures and exhibit high dilation.

4 MACROSCALE OBSERVATIONS - SOILS

The angle of internal shear strength ϕ in soils reflects the contributions of mineral friction at contacts μ (and associated microscale mechanisms including pore fluid effects), particle rearrangement, dilation, and rotational frustration. The angle of internal shear strength in soils can be established at different stages in the load-deformation response. These are related to the strain level, and the mechanisms that are involved. A brief discussion follows, with emphasis on strain level, trends and difficulties (a comprehensive review is presented in Mitchell, 1993).

Friction at maximum shear strength (when σ_1-σ_3 is maximum). This value is attained at a strain level between 1% and 10%. It includes the contribution of dilation and interparticle friction (Taylor, 1948; Rowe, 1962; Bolton, 1986).

Friction at maximum obliquity (when σ'_1/σ'_3 is maximum). It is different and higher than the previous value in contractive soils subjected to undrained shear, and it would be observed at a strain level higher than the peak.

Friction at constant volume (or at critical state), i.e., when dilation and contraction have reached global balance. It is attained at a local strain which is in the order of 100 % to allow particles to exchange neighbors and attain a condition of statistical equilibrium (in practice lower strain levels are used ~20%). Available experimental evidence suggests that the constant volume friction angle depends on mineralogy and particle shape (sphericity, angularity and roughness), therefore, it is not just mineral friction.

Friction at particle alignment or residual friction angle. This is observed in soils that contain particles with eccentricity, especially platy particles. The residual strength is attained at large strain deformation (excess of 100%), when particles become aligned with respect to the failure plane. The residual strength is dependent upon content of eccentric particles (must exceed 10-25% by weight) and the mineralogy, such as biotite, kaolinite or smectite. (Skempton, 1964 and 1985; Lupini, Skinner and Vaughan, 1981)

Dilation. Following Taylor (1948), dilation ψ and constant volume friction ϕ_{cv} add to the measured soil friction ϕ, $\phi=\phi_{cv}+\psi$ (see Bolton, 1986). Dilation decreases with the increase in confinement and/or the increase in porosity (early work by Casagrande 1936 and Bishop 1950). The result is a curved failure envelope for peak strength, $\tau_f(\text{peak})=\alpha\sigma'^{\beta}$. Note that the maximum rate of dilation coincides with the maximum strength in uncemented dense soils. This is not the case in cemented soils, where dilation starts as the peak strength is overcome; this is often the case in highly OC clays (Terzaghi, et al 1996). Dilation can be a very important component of shear strength. Dusseault and Morgenstern (1979) tested locked sands and measured $\phi=65°$ peak friction angles, $\phi_{cv}=34°$ constant volume angles, and $\psi\sim31°$. Sture et al. (1998) have measured equally high values. As confinement increases, grain crushing takes place, yet, it appears that crushing does not affect friction (Vesic and Clough, 1968; Coop, 1999).

Strain localization. Soils that exhibit post peak strength softening tend to experience strain localization. The resulting shear bands are oriented in relation to the peak strength friction angle. Therefore, data analysis must take into consideration the orientation of the shear plane, as in a jointed rock, when computing the constant volume and the residual friction angles.

Intermediate stress. The value of the friction angle varies with the effective stress anisotropy and the intermediate stress captured in the b-coefficient, $b=(\sigma_1-\sigma_2)/(\sigma_1-\sigma_2)$; typically (Mayne and Holtz, 1985),

$$\phi_{DSS} > \phi_{AE} \approx 1 \text{ to } 1.5\,\phi_{AC} \qquad (1)$$

The microscale explanation is based on the evolution of interparticle coordination, the development of rotational frustration, and the need to cause slippage to continue deforming (review and interpretation in Santamarina, 2002).

Plasticity – Fineness. The friction angle decreases with the increase in plastic index IP in most soils as (Figure 2),

$$\phi = [46 - 12.5\log(\mathrm{IP})] \pm 6 \qquad \text{[in degrees]} \qquad (2)$$

The following sequence of correlated observations applies: the higher the plasticity index, the smaller the grain size, the thinner the particles, the lower the skeletal force each particle receives, and the higher the relevance of long range electrical forces such as osmotic repulsion. Atomic scale evidence discussed earlier suggests that the existence of friction in fine grained soils requires interparticle distance smaller than ~10 Å. Both physisorbed and chemisorbed conditions are expected to contribute. Observed strain-rate effects follow from microscale observations (Figure 1).

Pore fluid, fabric and void ratio. Surface charge, double layer thickness and fabric formation depend on pH and ionic concentration and valence in aqueous fluids, and on the permittivity of the pore fluid (important in non-aqueous fluids). In particular, high ionic concentration promotes face-to-face aggregation, while low ionic concentration and pH near the isoelectric point promote edge-to-face flocculation. Studies with single-mineral soils show that (compiled from the work by Mesri, Olson, Sridharan, Moore, di Maio, Burns, Warkentein, Yong and their co-workers among others – a comprehensive list of references is available from the authors):

- at a given effective confinement, friction increases when permittivity decreases, ionic concentration increases or the valance increases. (Note: the void ratio and fabric are not the same for soils with different fluids).
- flocculated clays exhibit higher shear strength than dispersed clays at the same void ratio.

Not all the available data are fully consistent with these trends. Specimen preparation, pore fluid characteristics and the conditions when pore fluid is exchanged can play an important role in such measurements because of their effect on fabric, pore size distribution, volumetric changes and stress relaxation. In general, a linear relation can be identified between soil strength and the number of bonds (Mitchell 1993, and references therein). Special caution must be practiced when interpreting peak undrained strength data, as its response is critically affected by internal spatial variability.

5 SOILS WITH ANOMALOUS FRICTION

The correlation between friction angle and plastic index is captured in Figure 2. The schematic trends summarize data presented by Mitchell (1993) and by Terzaghi et al. (1996). On the same plot, data are presented for high plasticity soils that deviate from these trends and exhibit high friction angle. These include:

- Ariake Clay "AC" (Japan. Tanaka et al. 2001; Ohtsubo et al., 1995). Marine, smectite, clay fraction 50%, diatoms.
- Bangkok Clay "BC" (Tanaka et al. 2001). Normally consolidated marine clay, smectite, clay fraction 50%, pellets.
- Bogota Soil "BS" (Moya and Rodriguez, 1987). Volcanic, lacustrian. Kaolinite, montmorillonite and diatoms.
- Cooper Marl "CM" (Charleston, USA. Camp et al. 2002). Marine, soft, very fine grained (≤ 0.002 mm) impure carbonate deposit with fossils (foraminifers).
- Mexico City Soils "MC" (Diaz-Rodriguez et al. 1998; Diaz-Rodriguez et al. 1992). Volcanic, lacustrine. Montmorillonite and illite, clay fraction 20-55%. Silica polymorphs (e.g., biogenic opal, cristobalite). Microfossils (diatoms and ostracods).

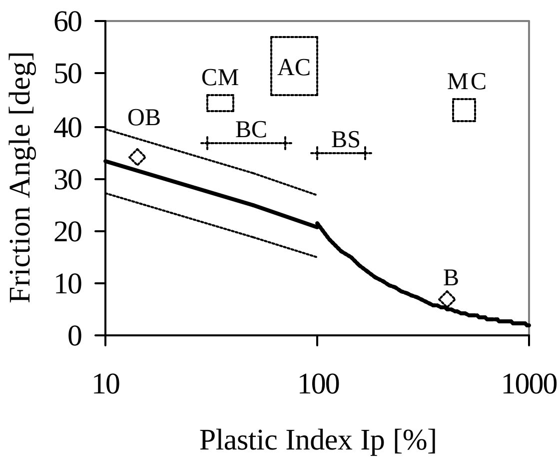

Figure 2 Friction Angle vs Plastic Index - Anomalous soil response. Diamonds: study of organo-clays (see text for details).

All these soils show evidence of biological activity during the formation history, as documented in the fossil record (diatoms, foraminifers, pellets). It has been observed that diatoms have an important effect on the behavior of soils (Day, 1995; Shiwakoti et al. 2002). On the one hand, the presence of diatoms increases the porosity of the soil and its ability to retain water; therefore the plastic index increases. On the other hand, diatoms are rough and increase interlocking effects. The two effects combine to shift measurements to higher IP and higher ϕ values.

Data for a bentonite mixed with water "B" and treated as an organo-bentonite "OB" are shown as diamonds on Figure 2 (Soule and Burns, 2001). While the same soil responds is drastically different ways, both results satisfy the overall trend. Clearly, low permittivity reduces the plasticity of the soil (does not hydrate clays or salts) and increases interparticle interaction by preventing osmotic repulsion (complementary studies can be found in Sridharan, 2001).

6 CONCLUSIONS

The fundamental understanding of friction and its control have experienced well-marked stages through history. Significant developments in the last two decades have set the stage for a new understanding of friction between surfaces (atomic force microscopy and molecular dynamic simulations) and within particulate materials (particle-level experimentation and discrete element modeling).

The frictional strength of soils is affected by stress anisotropy, pore fluid characteristics (organic and aqueous solutions), particle shape and packing density.

The nature of friction in fine grained soils has been justified from fluid viscosity and from solid-to-solid interaction. Atomic-level evidence indicates that the interparticle distance must be less than ~10Å to mobilize frictional resistance.

The friction-plasticity trend is robust, even when organic fluids are taken into consideration. Several soils deviate from this trend, in particular, some fine-grained soils exhibit surprisingly high friction. The fossil record in these soils confirms extensive biological activity during formation (diatoms, foraminifer, pellets).

It can be anticipated that the new, enhanced understanding of mineral and soil friction will lead to new developments in "engineered particulate materials" with enhanced friction control.

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