Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

The difficult task of teaching shear strength of soils

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Technical Note

Keywords
Geotechnical education
Shear strength
Mohr-Coulomb

Abstract

Shear strength is a classical topic in Soil Mechanics and generally there is little concern about the inconsistencies behind the theories used to predict its value. In fact the debate on this issue is rather limited as the geotechnical community considers this a well-established concept. This note intends to highlight the difficulties that arise when teaching that concept in an undergraduate Soil Mechanics course. Those difficulties are related to the drained/undrained behavior of soils, but also to the fact that cohesion is a tricky parameter, with a misleading physical meaning, depending not only on the properties of the contacts between particles, but also on external conditions (i.e., saturation or unsaturation). All these aspects are not analyzed in detail in many textbooks, but they should be considered in a modern Soil Mechanics course.

1. Introduction

Soil Mechanics is a typical subject in most of the Civil Engineering degrees everywhere. Also, most of the Mining degrees and some Architecture Engineering degrees include some Soil Mechanics topics in the curriculum. In general, students in the Civil Engineering Schools attend a lot of courses on Mechanics and Structural Engineering, following the traditional organization from the oldest Civil Engineering Faculty in the world: the “École Nationale des Ponts et Chaussées”, founded in Paris in 1747. A few specific courses on Soil Mechanics were implemented later, during the 20th century, in the Civil Engineering Schools. However, nowadays, typically, there are fewer courses on Soil Mechanics and Geotechnical Engineering than courses on Concrete or Steel technology.

It is obvious that Soil Mechanics uses many concepts from other disciplines as Continuum Mechanics or just Mechanics, but the material involved, soil, is particularly different from other materials used in construction, and this is quite difficult for students when comparing soil properties with concrete or steel. Some of the differences are:

- Soils are natural materials. There is not any quality control on their mechanical properties (as in a man-made material), so diversity and heterogeneity are inherent features;
- Soils have been in nature for many years (thousands…), undergoing mechanical changes (and even chemical changes). They may have been loaded and unloaded and they have initial stresses before being loaded further due to construction;
- Soils are not elastic materials, that is, they do not behave in a reversible manner. Loading and unloading processes must be carefully analyzed working in increments of stresses and strains;
- Soils do not have constant mechanical properties in general. The same soil has mechanical properties depending on confinement, that is, depending on depth;
- Pore water pressure has much influence on soil properties as soil is a porous medium. Students find difficult to realize that for a particular soil at a particular depth, strength is not constant, but depends on pore water pressure as well, a quantity that is essentially variable;
- Soil strength depends on strains also, and the same clay may behave as a ductile or as a brittle material, depending on the past loading and unloading history.

Considering all these aspects, shear strength is a mechanical concept that is particularly difficult to teach properly to the students (Pantazidou, 2015). However, there is not much debate on that and the teaching resources available, in general, do not focus on those difficulties, which arise from the fact that the procedure used to estimate shear strength and related concepts are not very precise. In several provocative papers, Schofield (1998a, b), suggested that Coulomb theory included an error. Surprisingly, the comments on this among the Geotechnical community are scarce. Schofield referred to the physical interpretation of the cohesion and friction terms in the Mohr-Coulomb strength criterion, a point that is discussed below.

2. The Mohr-Coulomb strength criterion

The classical Mohr-Coulomb criterion, accepted today as the fundamental law for soil shear strength in saturated conditions, is the result of the evolution of the initial idea

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Submitted on April 24, 2024; Final Acceptance on April 29, 2024; Discussion open until August 31, 2024.
https://doi.org/10.28927/SR.2024.003424

from Coulomb, back in 18th century. Coulomb considered the thrust on gravity retaining walls working with forces (the concept of stress was not defined yet), and solved the limit equilibrium problem of a failure wedge determining the true position of the sliding surface using calculus concepts for maxima and minima. His paper from 1773 was recently reprinted in the Revue Française de Géotechnique (Coulomb, 2023) and has been analyzed by several authors as Heyman (1972), Schofield (1998a, b), Salençon (2022) and Lacasse (2023), among others.

Coulomb assumed that the soil strength had several components: adhesion, cohesion and friction, but the definition of each component was not very precise (translation to English by Salençon (2022):

- “Friction and cohesion are not active forces such as gravity that always fully exerts its effect, but only coercive forces; those two forces are assessed through their limits of resistance”;
- “The resistance due to friction is proportional to the pressure exerted”;
- “Cohesion is measured by the resistance that solid bodies oppose to the direct disunity of their parts”;
- “Adhesion forces are equally resistant whether they are directed parallel or perpendicular to the fracture plane”.

Coulomb did some experiments with rock and he used the word “adhesion” when referring to experiments in tension, and “cohesion” for shear failure conditions. However, he measured similar values for both concepts. He also realized that remoulded soils should have zero cohesion or adhesion. Coulomb continued for several years his experiments on friction (Kerisel, 1973).

About 50 years later, Cauchy developed the concept of stress and eventually Mohr, about 1882, defined the graphical construction that allows obtaining the stress state at a point, acting on any plane: the Mohr circle.

Later, in 20th century, Terzaghi proposed the current version of the Mohr-Coulomb criterion. He kept the same structure of the formula: a constant term called cohesion and a term that depends linearly on the normal stress due to friction. However, he introduced the effective stress in the computation of the normal component. That is, the limit shear stress (strength) acting on a plane can be computed as:

$$\tau = c' + \left(\sigma - p_w\right)\tan\varphi' \tag{1}$$

where τ is the maximum shear stress (strength), σ is the normal stress (perpendicular to the sliding plane), p_w is the pore water pressure, c' is the cohesion and φ' the internal friction angle.

The term $\tan\varphi'$ represents a friction coefficient. Note that c' and φ' should be measured in the laboratory under drained conditions and this is why traditionally the superscript (’) is used for c and φ. The effective stress, σ', is defined as $\sigma'=\sigma - p_w$. Classical Soil Mechanics sign convention is used here, that is compressions for stresses and water pressure are positive (Terzaghi, 1925, 1936, 1943).

Terzaghi tried to define more precisely the physical meaning of cohesion and friction angle. On the one hand, the tangent of friction angle is equivalent to a friction coefficient, as already defined by Coulomb and others. The use of that angle was adopted because it follows from the slope of the geometric line tangent to the Mohr circle. Also, the friction angle was related to the angle of a slope of dry granular soil at limit equilibrium (angle of repose). On the other hand, cohesion is a bond between particles (Terzaghi, 1943). Within this context the words “cohesive soil” or “cohesionless soil” were used as a simple soil classification. Cohesive was synonymous of clay and cohesionless of sand, a classification still used today in daily practice and as a nomenclature in codes and standards. Nowadays we know that these words are not precise as it is examined below.

3. The approach from Taylor (1948)

Taylor, in 1948 published a book entitled “Fundamentals of Soil Mechanics” which is a good reference to analyze the knowledge on this topic at that time. Some of the concepts already presented in Terzaghi’s book from 1943 are shown in a different manner. Cohesion is one of those concepts.

Taylor indicates that the basic mechanism responsible for shear strength is friction, and it needs an external pressure or stress to be active. But some materials “have strength which cannot be attributed to any visible source of pressure… This condition often may be described as a result of a pressure which was exerted on the material at some time in the past, the effects of which have in some way been retained”. Taylor refers to overconsolidated clays and to experiments showing cohesion that he relates to the capillary pressure induced when extracting the sample from the field (that is, unloading the sample and generating water tension). He proposed to call that strength “apparent cohesion”. Some clays, however, maintain some “internal pressure” and have some type of bonding, exhibiting a “true cohesion”, as for instance most sedimentary rocks.

When dealing with sands, Taylor considers the results of direct shear tests on dense and loose samples. Dense sands dilate and have a peak strength and a final strength (usually defined today as constant volume strength). Loose sands have just a final or constant volume strength (Figure 1). Taylor assigns the extra strength of dense sands to the effect of interlocking, whereas friction is responsible for that constant volume strength. Each shear strength, either peak or constant volume, would correspond to a different value of the friction angle.

Taylor (1948) concluded that the experiments allow to define an envelope of the soil shear strength (Figure 2). For overconsolidated clays, tested at low stresses, a peak strength is observed, and an envelope is clearly defined on

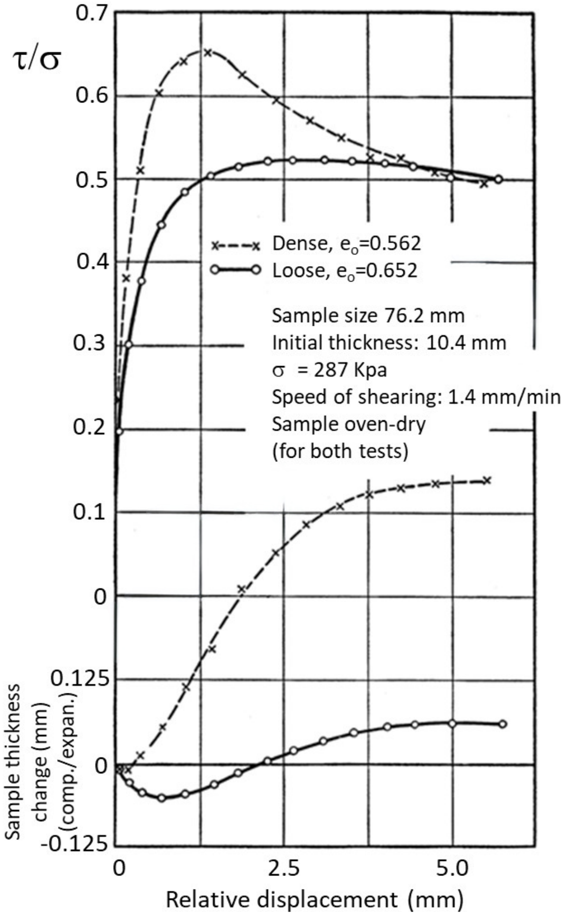

Figure 1. Direct shear experiments on Ottawa sand (modified after Taylor, 1948).

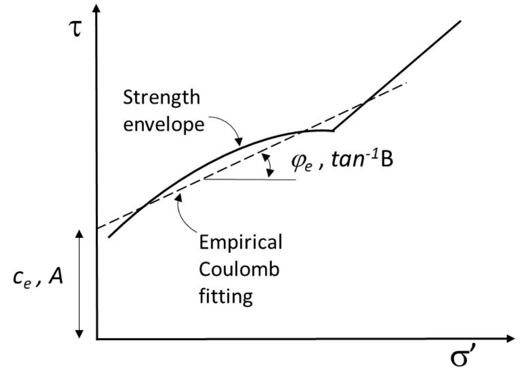

Figure 2. Interpretation of Coulomb's empirical law (modified after Taylor, 1948).

the left hand side of Figure 2; whereas the same clay, when tested at higher stresses (on the right hand side of Figure 2), shows a strength directly proportional to the effective stress. Coulomb's law is just a linear fitting of that envelope:

$$\tau = A + \sigma' B \tag{2}$$

where τ is the shear strength, σ ' is the effective stress and A, B are fitting parameters.

The words cohesion and friction angle are used traditionally for the coefficients of that line, but they are essentially fitting parameters of an empirical law. Taylor proposes to use the words "effective cohesion, c_e" and "effective friction angle, φ_e",

$$c_e = A \; ; \; tan\varphi_e = B \tag{3}$$

but warns about their values in this way: "[…] [they] are not constant soil properties but are empirical coefficients which may vary over wide ranges for a given soil under the various possible conditions of precompression, drainage, and other variables" (Taylor, 1948).

This rational is different from the approach typically observed in textbooks. Cohesion and friction angle are not conceptual soil parameters, but fitting coefficients that may have a wide range. Shear strength depends on so many factors and mechanisms, that it is more convenient to present those "parameters" not as fundamental concepts, but as empirical coefficients.

Schofield has published several papers highlighting the weakness of considering cohesion and friction as fundamental soil parameters corresponding to physical properties (Schofield, 1998a, b, 2001). Cohesion and Friction do exist as mechanisms providing strength, but they are not always active or they depend on external factors. Interlocking as defined by Taylor (1948) is another mechanism that may be active as well and should be taken into account (Schofield, 2001).

4. Residual shear strength

There is another strength that should be considered in clayey soils: the residual strength. That strength is due to the friction between clay particles when they become oriented after large strains. Although the idea of a residual low friction in the context of catastrophic landslides is quite old, the initial works measuring that strength by means of a ring shear apparatus are attributed to Hvorslev (1936). The experiments showed clearly that clay strength is a strain-dependent concept and there is not a unique strength for soils. This is indeed a challenge, as it is difficult to predict strength without considering the strains, that is, with an appropriate soil constitutive model. A classical approach in Mechanics is based on predicting limit forces or stresses when considering ultimate states, and estimating displacements under serviceability conditions, using elasticity for the sake of simplicity. That is, traditionally, ultimate states are predicted without considering strains; however, this approach oversimplifies soil behavior.

If the Mohr-Coulomb criterion is used to predict strength, then it is required to define different sets of cohesions and friction angles, for peak strength, for constant volume strength and for residual strength.

5. Undrained shear strength

Another strength can be defined for clayey soils when there is not drainage upon loading. It is the undrained shear strength. Under undrained conditions, there is an increment, positive or negative, of pore water pressure due to the external load (part of the load is "taken" by water). This increment is difficult to predict in general and thus, it is difficult to compute effective stresses and to evaluate the soil shear strength according to the Mohr-Coulomb Formula 1. As a consequence of this, it is almost inevitable to use total stresses, and therefore we have to change the Mohr-Coulomb criterion because it is defined in terms of effective stresses.

If total stresses are used and there are not water content changes (undrained conditions), the strength of clays can be predicted as:

$$\tau = c_u \tag{4}$$

where τ is the maximum shear stress (strength) and c_u is the undrained shear strength.

This is in fact a Tresca type strength criterion. Comparing Expression 4 with Equation 1 suggests that in undrained conditions it is like having a cohesion equal to c_u and a zero friction angle. Obviously, this is just a mathematical interpretation, but not a physical one.

The idea of using this type of strength criterion is attributed to Fellenius in 1922 (reported by Skempton, 1948). Fellenius computed the stability of clay slopes using limit equilibrium conditions assuming pure cohesion and $\varphi = 0$. Different authors, including Terzaghi, confirmed that assumption experimentally later. Skempton (1948) presented a revision on this and some application to real cases, and explicitly he warned on the use of $\varphi = 0$:

- This strength criterion only applies when there is not water content change in the saturated soil during loading (that is undrained conditions);
- The true friction angle is not zero. The behavior is controlled by the true cohesion, the true friction angle and the effective stresses;
- This $\varphi = 0$ cannot be used if soil is unsaturated.

It becomes evident that using $\varphi = 0$ is just a mathematical trick, and Skempton (1948) is aware of that when concluding: "It may be possible to evolve an analysis which overcomes the difficulties expressed … Meanwhile, provided its limitations are appreciated, the $\varphi = 0$ analysis is a method of great value in civil engineering design".

When teaching Soil Mechanics, one of the fundamental concepts is the idea of effective stress, a concept that is usually presented at the beginning of a course. The mechanical behavior of a saturated soil depends on the effective stress changes, and therefore, a "correct" analysis even in undrained conditions should be carried out in terms of effective stresses always. However, at this point we have to recognize that the effective stress is very difficult to compute in undrained conditions, due to the unpredictable pore water pressure change. Some expressions have been historically proposed to predict the pore water pressure increment in undrained conditions (e.g. Skempton (1954) formula, Henkel (1960) formula) but they are not very good in general as water pressure increments are nonlinear and depend on many factors.

As a compromise solution, only for this case, it is possible to use total stresses if the strength criterion is changed: using (4) instead of (1). The difficulty of predicting pore water pressure is avoided, but now we have to estimate c_u, which has proven to be simpler. In fact, the geotechnical community realized soon that c_u is half of the unconfined compression strength of the clay (Skempton, 1948). In fact, c_u is equivalent to the deviatoric stress (using Lambe's variables) at failure: $q_{Lambe} = (\sigma_1 - \sigma_3)/2$. There are also many empirical expressions relating c_u with other soil properties: plasticity index, confinement and loading history (normally consolidated or overconsolidated).

Figure 3 shows a typical stress plane with the effective stress paths of four conventional triaxial tests from a low plasticity clay (Gens, 1982), at different confining stresses, with and without drainage. The undrained shear strength, c_u, is half the Cambridge deviatoric stress at failure: $q_{Camb} = \sigma_1 - \sigma_3$. Note that all experiments (drained and undrained) finish on a final strength line if effective stresses are used. In this case, that line passes through the origin (zero cohesion) and with

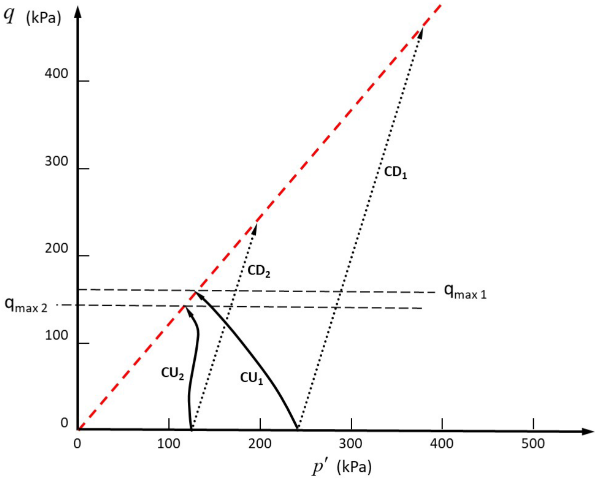

Figure 3. Effective stress paths of four triaxial tests from the same clay: undrained tests (CU_1 and CU_2) and drained tests (CD_1 and CD_2). Sample 1 is normally consolidated and sample 2 oversonsolidated. Cambridge variables: $q = \sigma'_1 - \sigma'_3$, $p' = (\sigma'_1 + 2\sigma'_3)/3$, where σ'_1 and σ'_3 are the major and minor principal effective stresses. $q_{max\,1}$ and $q_{max\,2}$ are the undrained strengths obtained for samples 1 and 2, using Cambridge variables, that is, $c_u = q_{max}/2$. (modified after Gens, 1982).

a slope related to its friction angle. Soil fails in undrained conditions when the effective stress paths reaches that final strength line. However, we know this effective stress in the laboratory as we can measure pore water pressure, but it is not the case in the field, and we need to work with total stresses and with the undrained shear strength. Note that two samples of the same clay do not have the same undrained shear strength, that is, for the same clay, c_u depends on the confining stress before the loading path of the triaxial test. For a layer of a normally consolidated clay, c_u depends linearly on depth, as confinement increases linearly with depth, being theoretically nil at ground surface.

Designing geotechnical constructions with a value of c_u increasing linearly with depth is cumbersome and most of the books and exercises consider a constant value for a layer. In addition to that, close to the ground surface the undrained shear strength is not zero in practice, mainly due to unsaturation. Considering constant undrained shear strength is a matter of convenience and generates confusion to students.

Definitely, the concept of c_u is a sort of escape route in undrained conditions. The idea that it is a compromise because we don't know how to compute effective stresses in undrained loading, should be clearly exposed to students.

Modern numerical methods as finite elements are able to solve the coupled hydro-mechanical problem representing the solid-fluid interaction in the soil, so a prediction of the pore water pressure can be attempted in undrained problems nowadays. Nevertheless, that prediction is very sensitive to the constitutive model considered. As an example, the collapse of Nicoll Highway in Singapore in 2004, was mainly due to an overestimation of the undrained shear strength computed using a finite element code and an elastic Mohr-Coulomb model for the soil working in effective stresses (Puzrin et al., 2010). That model has been very popular in the past, but behaviour of the clay was not elastic before failure and that model does not predict any water pressure increment in pure shear, resulting in a large unrealistic undrained shear strength. Therefore, the use of a total stress analysis, although not very consistent with Soil Mechanics fundamental principles, is still very convenient in practice. As indicated by Skempton (1948), "meanwhile the $\varphi = 0$ analysis is a method of great value in civil engineering design".

6. The contribution of Critical State Soil Mechanics

In 1968 the book by Schofield & Wroth (1968) established a starting point for a new development in the understanding of soil behaviour. The general theory of plasticity and in particular, the Cam-clay model, were able to reproduce the results from triaxial tests on both normally consolidated and overconsolidated clays. Before that, it was quite common to distinguish these types of soils as different materials. On the one hand, normally consolidated clays are ductile and they experience volume reduction when shearing under drained conditions. On the other hand, overconsolidated clays are brittle, they show a peak and a constant volume strength, and they dilate (increase volume) when shearing in drained conditions. Traditionally each type of clay was a different chapter when teaching Soil Mechanics. With the Cam-clay model, the same clay, with the same parameters, can behave ductile or brittle, depending on the loading history. Cam-clay model was able to simulate both behaviors with a unique set of parameters. Conceptually this is very important and it is also useful for teaching purposes. The model is a bit more complex than using elasticity or just Mohr-Coulomb, but it is a consistent framework to reproduce soil behaviour and facilitates the understanding. Figure 4 presents a sketch of the yield surface of the modified Cam-clay model showing the stress-strain behaviour of two samples, one normally consolidated and another one overconsolidated following a drained triaxial test. The strength envelope predicted with the modified Cam-clay model is consistent with the considerations of the soil shear strength indicated in previous sections.

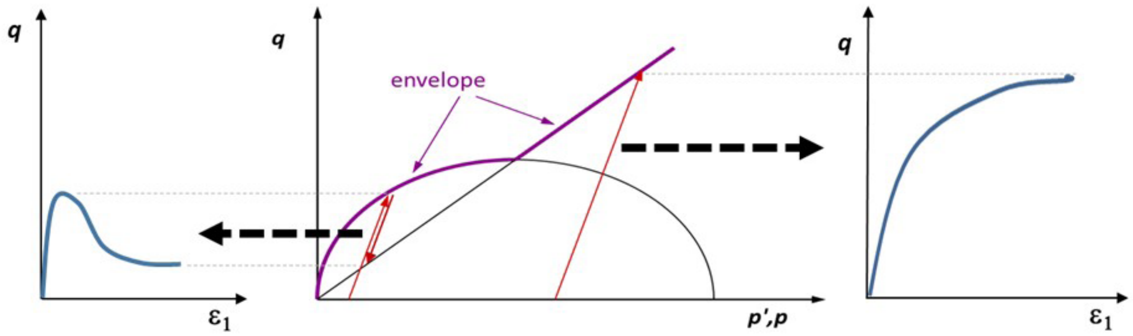

Figure 4. Sketch of the yield surface of the modified Cam-clay model and two drained triaxial tests, showing the deviatoric stress (q) - strain (ε_1) curve predicted for a normally consolidated clay (right) and overconsolidated clay (left).

7. The Unsaturated Soil Mechanics approach

A modern version of a Soil Mechanics course should include at least a brief description of the effects of unsaturation on the mechanical behaviour. The books by Terzaghi (1943) and Taylor (1948) include already a chapter on capillarity. Obviously there has been much scientific development since then.

Although there have been proposals to define generalized effective stress for unsaturated soils (Jaksa, 2020), it is accepted that two variables are required to characterize unsaturated soils, i.e., net stress (total stress minus air pressure) and suction (air pressure minus water pressure). Fredlund et al. (1978) extended the Mohr-Coulomb shear strength criterion for unsaturated conditions, in which a "cohesion term" dependent on suction was considered:

$$\tau = c' + s \tan \varphi^b + \left(\sigma - p_a\right) \tan \varphi' \tag{5}$$

where s is suction, p_a is air pressure and φ^b is a soil parameter.

This is consistent with observations in nature: a clean dry or immersed sand is cohesionless ($c' = 0$), but under partial saturation shows cohesion due to the term [$s \tan \varphi^b$] in (5). This is the key factor when constructing sand castles in the beach! However, this cohesion is just apparent, as it can be lost if sand is wetted.

Clays in general have zero cohesion, as there is not any bond between particles. However, when taken from the field, they develop suction, event at saturations above 99% and therefore an apparent cohesion is generated. Assigning the adjective "cohesive" to clays is misleading because it is not a "true" cohesion. The adjectives "cohesive" and "cohesionless" should not be used in textbooks and codes. "Fine" and "granular" or "coarse" soil should be used instead (Burland, 2012).

The Cam-clay model can also be generalized to account for the unsaturation (Alonso et al., 1990). Here the theoretical background is more complex. Suction is included as an additional variable and the yield surface (that is the elastic region) increases with suction. Figure 5 shows a simple sketch of the extended yield surface of the so-called Barcelona Basic model. The strength envelope is expanded as suction increases. The details of the model may not be appropriate for undergraduate courses, but it is a good framework for a Master course.

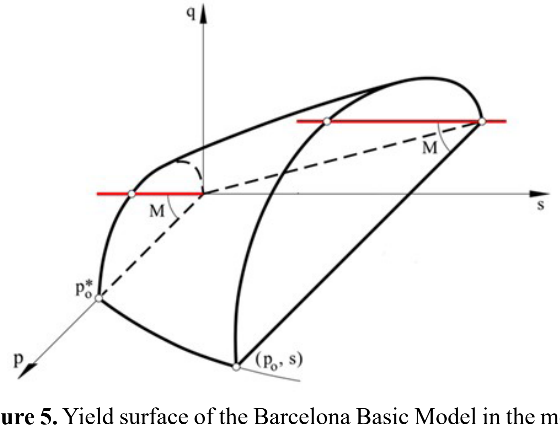

Figure 5. Yield surface of the Barcelona Basic Model in the mean net stress (p) – deviatoric stress (q) – suction (s) space. M is the slope of critical state line (modified from Alonso et al., 1990).

8. Discussion and conclusions

Soil shear strength is not a simple concept, despite what most textbooks apparently present. In undergraduate courses there is a tendency to oversimplify this concept, presenting Mohr-Coulomb as the basic theory, but with many options that are a bit "magical". This is because cohesion and friction angle are assumed as conceptual parameters with physical meaning, but they change for the same clay depending on whether the strength is the peak strength or the constant volume strength or the residual strength or the undrained shear strength. Both, cohesion and friction, correspond to physical mechanisms that may contribute to shear strength, but they may be "active" or not for a particular soil under particular conditions (i.e., a cohesionless sandy soil exhibits some cohesion when unsaturated). Another mechanism that may contribute to strength is interlocking, as indicated by Taylor (1948). All these mechanisms correspond to well defined physical phenomena, but their contribution to shear strength depends on several factors, some of them external to the soil (as unsaturation, or loading history).

In an undergraduate Soil Mechanics course it would seem more convenient to consider a strength envelope and some fitting parameters useful for computations, but without a specific physical meaning. However, a physical meaning is better understood when the Cam-clay model is used to explain soil behaviour. Perhaps only in a Master's course there is time to present all the faces of the same concept: true cohesion, apparent cohesion, etc., but otherwise cohesion and friction angle are so variable that they are very difficult to transmit as fundamental soil parameters, mainly because strength depends on strain. The classical classification between cohesive and cohesionless soils is not appropriate, despite being used in most textbooks and standards. It is more convenient to use the words: "fine soils" and "granular soils". All of them can exhibit cohesion depending on external factors, so cohesion is a property that can be acquired or lost. Likewise, friction angle is a coefficient that could be even zero or may have several values depending on whether we have peak, constant volume or residual conditions. This idea should be conveyed in undergraduate courses and to do that properly, a conceptual framework as Critical State Soil Mechanics should be introduced. This is always a matter of debate, as undergraduate courses have many constrains. However, a modern view of Soil Mechanics should present an introduction to the Cam-clay model, to use its capacity to teach soil shear strength in a proper manner. Referring to general terms in the context of the Civil Engineering syllabus, the phenomenological aspects of the Plasticity theory should be understood at undergraduate level. It is not appropriate to present concepts without a supporting theoretical framework that is nowadays available, so we are committed to adapt those theories to the undergraduate level. Overall, this is why teaching soil shear strength is indeed a difficult task.

Declaration of interest

The author has not any conflict of interest to declare.

Data availability

No dataset was generated or evaluated in the course of the current study; therefore, data sharing is not applicable.

List of symbols and abbreviations

c'	cohesion
c_u	undrained shear strength
M	slope of critical state line
p	mean stress / net mean stress
p'	mean effective stress
p_a	pore air pressure
p_w	pore water pressure
q	deviatoric stress
s	suction
ε	strain
σ	normal total stress
σ'	normal effective stress
τ	shear stress / shear strength
φ'	angle of internal friction
φ^b	angle of friction for suction changes

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