Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190026

Fully Softened Shear Strength: Application, Measurement, and Correlations

Bernardo A. CASTELLANOS[a,1] and Thomas L. BRANDON[a]
[a] *Civil and Environmental Engineering Department, Virginia Tech, United States*

Abstract. The fully softened shear strength is an important engineering parameter for first-time slides in cuts in stiff clays, and in compacted clay embankments constructed using high plasticity clays. This paper presents a summary of the available guidelines to properly use this concept in slope stability analysis and to measure it in the laboratory. Updated correlations to obtain fully softened shear strength parameters using soil index properties are also presented.

Keywords. Stiff clay, fully softened shear strength, slope stability, first-time failure, compacted clay embankments, shear strength, slope stability analysis.

1. Introduction

The fully softened shear strength, has been defined as the drained shear strength of a clay in its normally consolidated state [1], has been empirically found to apply to first-time failures in cut slopes in stiff clays [2], compacted embankments constructed of high plasticity clays [3] and slopes in mudstone [4].

Sir Alec Skempton [1, 5, 6] developed this concept empirically in the 1960s by analyzing failures in cut slopes in stiff clays. These failures had the shared characteristics that they occurred a long time after the cut was made and the mobilized shear strength based on back analysis was considerably lower than the peak strength from undisturbed specimens. In the 1970s and 1980s, Prof. Steve Wright [7, 8] investigated failures in compacted embankments of high plasticity clays that had the same characteristics of time-delayed failure and lower mobilized shear strength as the failures analyzed by Skempton [1, 5, 6]. Based on those observations, Prof. Wright [7, 8] and his colleagues concluded that the fully softened shear strength is the controlling strength for these structures.

A significant amount of research has been performed in the last decade on the proper use and measurement of this empirical parameter [9–14] and correlations have been developed to estimate fully softened shear strength parameters using index properties [13–15]. This paper provides a summary of the research performed and presents an updated correlation to estimate fully softened shear strength parameters using index properties.

[1] Corresponding Author, Civil and Environmental Engineering Department, Virginia Tech, 23 Patton Hall, Blacksburg, VA 24060, USA, E-mail: bernardo@vt.edu.

2. Softening mechanisms

Different researchers have provided explanations for the decrease in shear strength with time for cuts in stiff clays and compacted embankments constructed of high plasticity clays. The mains explanations given are: (a) Fissures [16–19], (b) weathering [8, 20], (c) progressive failure [21–24], and (d) creep [6, 18, 25].

Based on a literature review and back-analysis of failed slopes, researchers have concluded that for cuts in stiff clays, it is very difficult to isolate one mechanisms as being solely responsible for the decrease in mobilized shear strength *in situ* for these types of structures [26]. Among the proposed explanations, progressive failure initiated by the stress relief following the excavation plays a major role in this type of failure. The other mechanisms play a secondary role but still affect the mobilized shear strength. For compacted embankments constructed of high plasticity clays, they suggested that strains caused by weathering initiate progressive failure causing the decrease in shear strength in this type of structures.

3. Time delay

Different theories have been proposed to explain the time component in the failures for cuts in stiff clays. Henkel [27], based on back analysis, concluded that a decrease in effective stress cohesion with time was a possible explanation. Later, Vaughan and Walbancke [28] measured pore pressures below steady state seepage values in a cut in Blue London Clay nine years after the cut was made, showing a slow dissipation of pore pressures after the cut was made.. These findings partially refuted the explanation presented by Henkel [27], and the delay in failure in cuts in stiff clays is due to the time required for the decreased pore pressures to reach their steady state value. For compacted clay embankments, where weathering is the main concern, the time delay is due to the multiple wet and dry seasons needed to decrease the shear strength.

Castellanos et al. [11] presented an assessment of 63 case histories of failures in cuts in stiff clays and 28 in compacted embankments of high plasticity clays [11]. Using those case histories, they showed that failures in compacted clay embankments usually occur in the first 20 years after construction while failures in cuts in stiff clays can take as long as 100 years after construction.

4. Use of fully softened shear strength

The applicability and use of the fully softened shear strength concept in slope stability analysis have been subject of discussions in many professional meetings and conferences, like the workshop held at Virginia Tech in 2011 [29, 30] and a special session at the 2013 ASCE Geocongress. As presented in previous sections, there is a time component in the decrease in the mobilized shear strength for cuts in stiff clays and compacted clay embankments. For this reason, the applicability of this concept to temporary structures (e.g. temporary excavations) is not justified in most cases and is left to the discretion of the engineer depending on the permanency of the structure.

Different factors have to be taken into account when applying the fully softened shear strength concept. The factors discussed in the following sections are: (a) type of soil, (b) pore water pressures, (c) shape of the failure envelope, (d) depth of softening, and (e) factor of safety.

4.1. Type of soils

Sixty-eight failures in stiff clays and 74 failures in compacted clay embankments related to fully softened shear strength were collected by Castellanos et al. [11]. Based on these case histories, they concluded that the fully softened shear strength concepts applies when the clays involved have liquid limits above 40 and plasticity indices above 20. They also stated that the stress history of the clay has an important role in the decrease in mobilized shear strength. In general, overconsolidated and compacted clays tend to become more brittle and have more diagenetic bonds as the overconsolidation ratio (OCR) increases [31]. For these reasons, these clays are more prone to experiencing a decrease in shear strength caused by processes like progressive failure and weathering.

4.2. Pore water pressures

Pore water pressures are one of the most important parameters in slope stability analysis, when using drained strength, that have direct impact on the calculated factor of safety. The pore pressures to be used in slope stability analysis are specific to each project and specific guidelines cannot be provided. Castellanos et al. [11] summarized the recommendations presented by several researchers and suggested that for cuts in stiff clays, a pore pressure ratio of 0.3 is adequate for preliminary designs if better information is not available [11]. For final designs, steady state seepage conditions representing the worst case scenario should be used. For compacted clay embankments, they recommended using pore water pressures corresponding to a water table coincident with the slope surface should for design if better information is not available.

4.3. Shape of the failure envelope

The fully softened shear strength failure envelope has been acknowledged to be curved by several researchers. The power function suggested Lade [32] has been used successfully to characterize this curvature. The equation for this function is presented below:

$$s = aP_a\left(\frac{\sigma'}{P_a}\right)^b \quad (1)$$

In this equation, s is the shear strength of the soil, a is equal to the tangent of the secant friction angle for an effective normal stress of one atmosphere, b is an empirical constant describing the curvature of the failure envelope, P_a is the atmospheric pressure, and σ' is the effective normal stress on the failure plane in the same units as the atmospheric pressure.

The assumed shaped of the failure envelope has been found to influence the calculated factor of safety [11], [30], [33]. Not taking into account the curvature of the failure envelope can increase the calculated factor of safety.

4.3.1. Depth of softening

The depth of softening, defined as how deep the fully softened shear strength should be assigned, was investigated by Castellanos et al. [11] using case histories found in the literature [11]. Castellanos et al. found that slides in stiff clays occur over a wide range of depths while in compacted clay embankments these tend to be shallow (less than 3.3m deep) [11].

4.4. Factor of safety

Factors of safety to be used in a given project are normally dictated by the code or standard used to design the structure. The factors of safety proposed by different agencies are tied to projects performed by that agency where the protocols for subsurface investigation, laboratory testing, and methods of analysis are standardized. The factor of safety for any project, should be based on the uncertainties associated with the parameters that control the design (e.g. shear strength and pore pressures) and the consequences of failure of the structure. For this reason, the factors of safety presented by Duncan et al. [34], summarized in Table 1, are recommended to be used. According to Castellanos et al., using fully softened shear strength parameters coupled with conservative assumptions of pore pressures results in small uncertainties in the analyses [11]. Based on Table 1, Castellanos et al. [11] recommended a factor of safety of 1.25 for shallow surfaces if the fully softened shear strength is coupled with pore pressures corresponding to the worst case scenario [11]. For structures with deep failures and low to medium consequences of failure, a factor of safety of 1.35 was recommended. For slopes with high consequences of failure, a factor of safety of 1.50 was recommended. The final design should be checked to verify that the factor of safety exceeds unity using residual strength.

Table 1. Minimum factor of safety recommendations[34].

Design Condition	Factor of Safety
Cost of failure < cost of more conservative design, AND Small uncertainty in soil and groundwater conditions	1.25
Cost of failure > cost of more conservative design, AND Small uncertainty in soil and groundwater conditions	1.50
Cost of failure < cost of more conservative design, AND Large uncertainty in soil and groundwater conditions	1.50
Cost of failure > cost of more conservative design, AND Large uncertainty in soil and groundwater conditions	2.00 or more

5. Measurement of fully softened shear strength

5.1. Sample preparation and specimen formation

Different sample preparation techniques have been proposed to process the samples for fully softened shear strength measurements. Researchers have ball milled, blenderized or processed the soil test specimens. Ball-milled samples refer to air-dried soil that is pulverized in a drum or vessel using special grinding media. Blenderized samples refer to samples that are mixed with water in a commercial blender until a slurry is formed. These two processes are normally performed before the soil sample is sieved through a

No. 40 (420 μm) sieve. It has been shown that processes like blenderizing and ball-milling influence the liquid limit and clay-sized fraction measured [9]. However, conclusive research has not been performed to investigate the influence of these processing techniques on the fully softened shear strength measured. Castellanos et al. [9] concluded that blenderizing does not greatly affect the fully softened shear strength measured [9]. Unless necessary, soil samples are recommended to be sieved as received through a No. 40 (420 μm) sieve to avoid any harsh mechanical processing on the soil.

5.2. Devices used

The fully softened shear strength has been historically measured using the direct shear and triaxial devices. In recent years, the ring shear device has been presented as a method to measure this shear strength. Castellanos and Brandon [35] presented a detailed laboratory testing program that showed that the direct shear and triaxial devices provide approximately the same results for the fully softened shear strength [35]. They also showed that the ring shear device provides very conservative values of fully softened shear strength and should not be used for this purpose. The triaxial device, even though capable of providing reliable values of fully softened shear strength, is very time consuming and very labor intensive to be use for this purpose. For these reasons, the direct shear device is the preferred and recommended method to measure the fully softened shear strength.

6. Correlation to estimate fully softened shear strength parameters

Different correlations have been presented in recent years to estimate fully softened shear strength parameters using soil index properties. Castellanos et al. [36] presented a detailed analysis of the existing correlations to estimate fully softened shear strength available in the literature[36]. Correlations are only as good as the data that was used to develop them. The authors have made an effort to only use high quality data when developing correlations and also made the data available to researchers for further scrutiny. Other published correlations do not allow user to assess the quality of the data that was used.

Castellanos et al. [36] presented correlations to estimate fully softened shear strength parameters as a function of the plasticity index (PI), and the clay-sized fraction (CF) times the PI using direct shear tests results on 46 soils [36]. Updated versions of these correlations, plus a new correlation relating the fully softened shear strength parameters using the fine content (FC) times the PI, are presented in Figures 1 to 3. Direct shear test results of 86 soils were used to develop the correlation presented in Figure 1, 78 soils for the correlation presented in Figure 2, and 69 soils for the correlation presented in Figure 3. In these figures, confidence limits obtained by decreasing the values obtained from the correlations by one or two standard deviations are also included

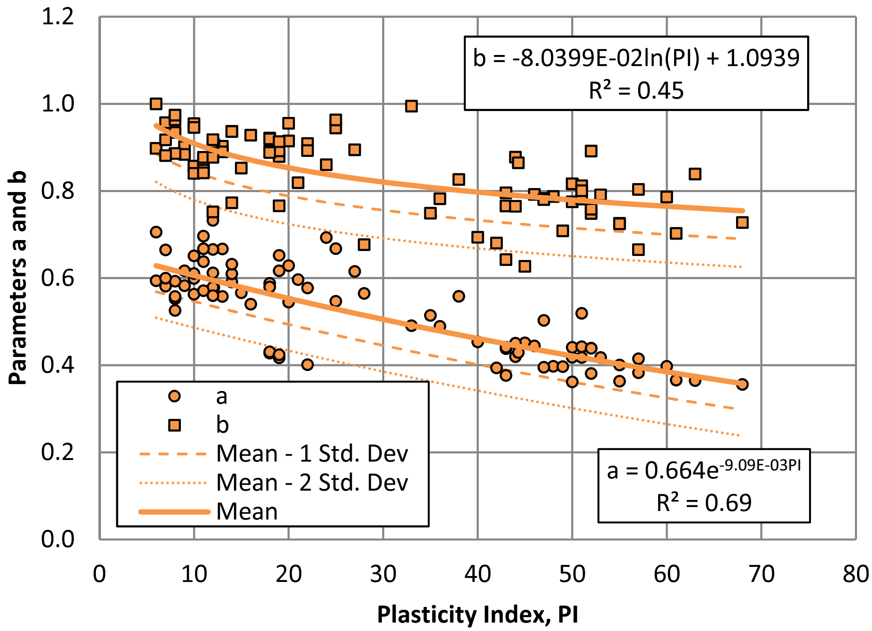

Figure 1. Correlation between the parameters a and b and PI.

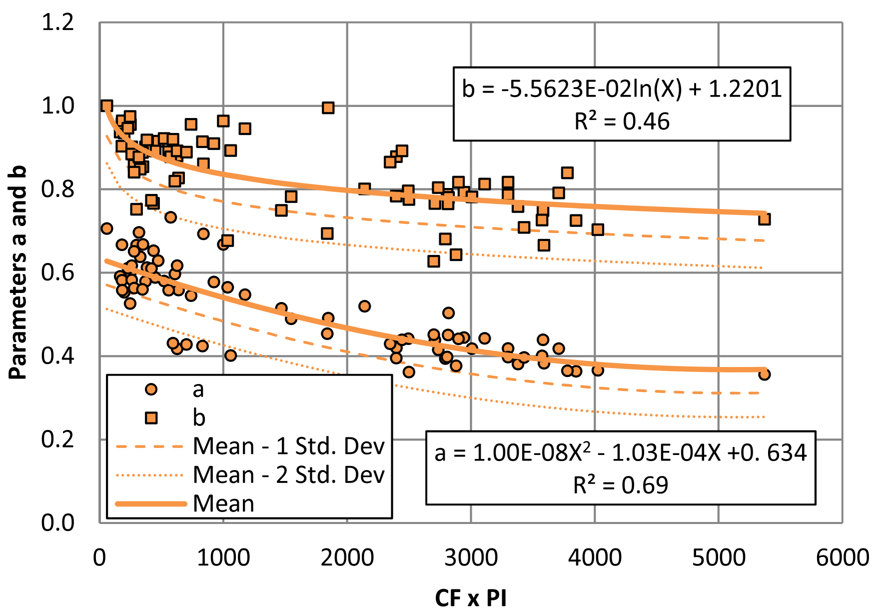

Figure 2. Correlation between the parameters a and b and CF x PI.

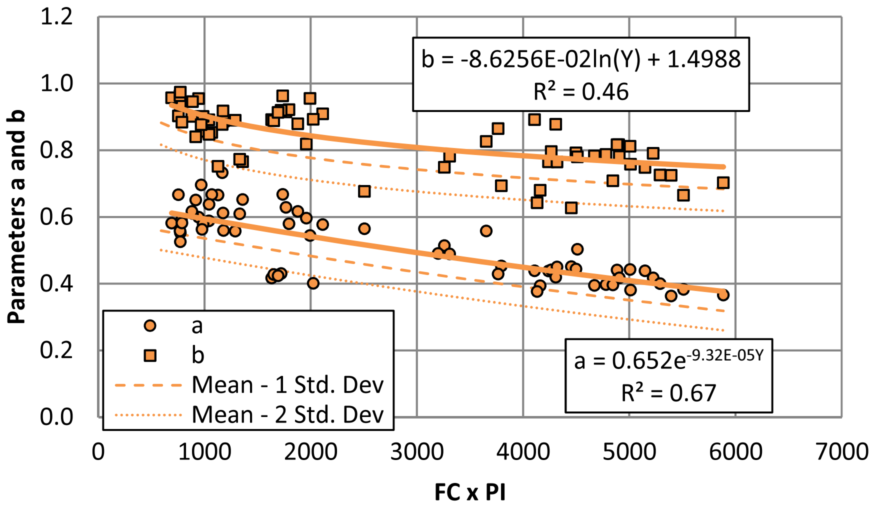

Figure 3. Correlation between the parameters a and b and FC x PI.

7. Conclusions

The fully softened shear strength is an important engineering parameter that should be use for the design of cuts in stiff clays and compacted embankments constructed of high plasticity clays. A summary of the available recommendations for the use of this concept in slope stability analysis and how to properly measure it in the laboratory was presented. In addition, new correlations to estimate non-linear fully softened shear strength parameters based on soil index properties were developed.

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