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Estimating fully softened and residual shear strength parameters of fine-grained soils

Estimation des Paramètres de Résistance au Cisaillement Complètement Ramolli et Résiduel des Sols à Grains Fins

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ABSTRACT: Selecting the appropriate shear strength to be used in slope stability analysis is always a challenge in every project, especially in those involving fine-grained soils. For fine-grained soils, three drained strengths can be used: (1) peak, (2) fully softened, and (3) residual; and the factor of safety is highly dependent on the strength selected. The fully softened and residual shear strengths are important engineering parameters when doing drained slope stability analysis in projects involving fine-grained soils because both of these falls below the peak, with residual being the lowest strength. This paper presents correlations to estimate shear strength parameters for these two conditions using simple and inexpensive index tests. These correlations are based on high-quality tests using the most extensive database available to date of soils from all over the United States covering a wide range of index properties and soil types.

RÉSUMÉ : La sélection de la résistance au cisaillement appropriée à utiliser dans l'analyse de la stabilité des pentes est toujours un défi dans chaque projet, en particulier dans ceux qui impliquent des sols à grains fins. Pour les sols à grains fins, trois résistances drainées peuvent être utilisées: (1) niveau maximal, (2) complètement ramolli et (3) résiduel; et le facteur de sécurité dépend fortement de la résistance choisie. Les résistances au cisaillement entièrement adoucies et résiduelles sont des paramètres d'ingénierie importants lors de l'analyse de la stabilité des pentes drainées dans les projets impliquant des sols à grains fins, car ces deux éléments sont inférieurs au niveau maximal, la résistance résiduelle étant la plus faible. Cet article présente des corrélations pour estimer les paramètres de résistance au cisaillement pour ces deux conditions à l'aide de tests d'indice simples et peu coûteux. Ces corrélations sont basées sur des tests de haute qualité utilisant la base de données la plus complète disponible à ce jour sur les sols de tous les États-Unis couvrant un large éventail de propriétés d'indice et de types de sols.

KEYWORDS: shear strength, fully softened, residual, slope stability, clay embankments.

1 INTRODUCTION

The shear strength of clays has been a major research topic in geotechnical engineering since its conception. Several landmark papers have been published on this subject (e.g., Terzaghi 1936; Skempton 1964; Bjerrum 1967). The shear strength to be used in slope stability plays a major role in the factor of safety obtained. In clays, three shear strengths can be used for drained analyses: (1) undisturbed peak, (2) fully softened, and (3) residual, as can be seen in Figure 1. The fully softened shear strength was defined by Skempton (1970) as the peak drained shear strength of a clay in its normally consolidated state. This shear strength has been recommended to be used in first-time slides for cuts and compacted clay embankments for clays with liquid limits above 40 and plasticity indices above 20 (Castellanos et al. 2016b).

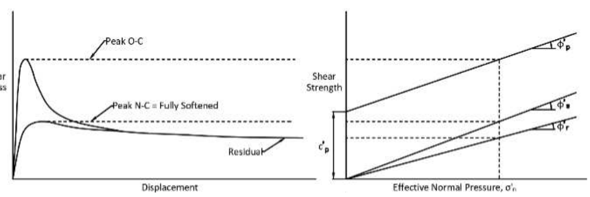

Figure 1. Three types of drained strengths of clays

Different mechanisms have been used to explain the reduction in shear strength towards the fully softened shear strength in compacted clay embankments and cuts in stiff clays. Some of these mechanisms are: (1) fissures (Terzaghi 1936; Marsland 1971), (2) creep (Mitchell and Soga 2005), (3) progressive failure (Chandler and Skempton 1974; Chandler 1984a; b; Potts et al. 1997), and (4) weathering, caused by cycles of wetting and drying, and freezing and thawing (Graham and Au 1985; Wright et al. 2007). A detailed discussion on these mechanisms was presented by Castellanos et al. (2016b). Castellanos et al. (2016b) concluded that a single mechanism cannot be isolated to explain this phenomenon and presented the fully softened shear strength concept to consider the combined effect of these mechanisms. Based on back analysis of failed slopes, they also concluded that for cuts in stiff clays, progressive failure might play a bigger role in the decrease in shear strength towards the fully softened shear strength and weathering for compacted clay embankments when compared to other mechanisms.

The residual shear strength is the shear strength of clays at large displacements. This shear strength is obtained when the clay particles align in a face-to-face orientation in the direction of shearing and further increase in displacement will not cause a decrease in shear strength (i.e. shear strength becomes constant). The residual shear strength is mainly used in reactivated landslides and zones subjected to previous tectonic movements. Also, some researchers have recommended this shear strength to be used on sections of the failure plane along bedding planes in first-time slides in stiff clays (Mesri and Shahien 2003).

2 LABORATORY TESTING PROGRAM

2.1 *Soils Tested*

An extensive laboratory testing program was undertaken at Virginia Tech to characterize the fully softened and residual shear strengths of clays. As part of this program, ninety-seven soils were tested using the direct shear device to measure the fully softened shear strength. These soils have liquid limits ranging from 22 to 102, plasticity indices ranging from 6 to 68, and clay-sized fractions from 10 to 79.

For the residual shear strength characterization, 102 soils were tested using the ring shear device. These soils have liquid limits ranging from 22 to 143, plasticity indices ranging from 6 to 112, and clay-sized fractions from 13 to 90. The amount of data collected in this testing program comprises the biggest consistent dataset available for fully softened and residual shear strengths to date. All the information about the soils tested and the laboratory testing program is presented in detail by Castellanos et al. (2021). From the map shown in Figure 1, it can be seen that the soils tested are geographically distributed in the United States.

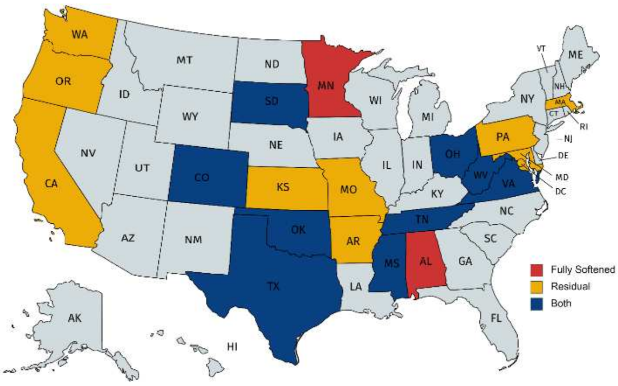

Figure 2. Location of samples tested.

2.2 *Sample Preparation*

Soil samples for fully softened shear and residual shear strength measurements were prepared in a similar fashion. The samples were sieved as received through a No. 40 sieve. This process usually requires soil samples to be washed through the sieve. After that, the samples were air-dried to a water content close to the liquid limit. The water content was deemed to be correct when 23-27 blows were required to close the groove cut in a Casagrande liquid limit test device.

Different disaggregation methods have been used in the past to process soil samples for fully softened and residual shear strengths measurements. Sometimes, samples have been blenderized or ball-milled prior to shear testing. These disaggregation procedures have been found to increase the measured liquid limit and clay-sized fraction but not to significantly change the measured shear strength (Castellanos et al. 2013). For the samples tested in this research, these disaggregation methods were not used on specimens used to measure the index properties. Some samples were blenderized prior to shearing and these have been identified by Castellanos et al. (2021).

2.3 *Devices Used and Testing Methods*

The fully softened shear strength has been historically measured using the triaxial and direct shear devices (Gibson 1953; Bishop et al. 1965; Skempton 1977; Cancelli 1981; Bhattarai et al. 2006; Wright et al. 2007). These two devices provides comparable fully softened shear strength envelopes as was shown by Castellanos et al. (2013). The ring shear device has also recently been used and an ASTM standard has been published for this purpose (ASTM D7608). Castellanos et al. (2013) showed that the fully softened shear strength envelope obtained with this device is very conservative. For this research, the direct shear device was used following ASTM D3080.

For residual shear strength measurements, the ring shear and direct shear devices have been used in the past. The direct shear device has some problems with particle alignment during shear reversals, extrusion, and others. For this reason, and the fact that infinite displacement in one direction can be applied in the ring shear device, this device is the preferred for residual shear strength measurements.

The ring shear device used in this research was the type designed by Bromhead (1979) with the modifications to reduce side-wall friction presented by Meehan et al. (2007).

The ring shear tests were performed in a multi-stage fashion where a single specimen is used to measure the residual strength at several consolidation stresses following ASTM D6467. When needed, additional soil was added to increase the specimen height, if significant compression occurred during consolidation.

After the soil samples were at the desired water content, the specimens were formed inside the specimen container of each device using a spatula. The consolidation process started with a low consolidation stress (5 kPa) to prevent extrusion of the specimen, and increased using a load increment ratio of one (i.e. the load was doubled) until the desired consolidation stress was achieved.

3 RESULTS

3.1 *Shear Strength Interpretation*

The curvature of the fully softened and residual shear strengths envelopes has been acknowledged by many researchers (Mesri and Shahien 2003; Wright 2005; Duncan et al. 2011; Castellanos et al. 2013, 2016a). The downward curvature of the fully softened and residual failure envelopes implies that the effective stress friction angle decreases with increasing stress. This nonlinearity is more pronounced at lower effective stresses. Pedersen et al. (2003) presented the results of tilt table tests performed at normal stresses ranging from 1 Pa to 2400 Pa that confirm the nonlinearity of the failure envelope going through the origin.

Several equations have been proposed to characterize the curvature of the failure envelope (De Mello 1977; Mesri and Shahien 2003; Noor and Anderson 2006; Lade 2010; McCook 2012). All of these equations can accurately model the curvature of the failure envelope, but some of these introduce more complexity than needed. The equation presented by Lade (2010), shown below, has been found to accurately model the curvature of the failure envelope using a simple form and parameters that are dimensionless.

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

Where:
$s =$ Shear strength of the soil corresponding to an effective normal stress σ',
$\sigma' =$ effective normal stress on the failure plane in the same units as the atmospheric pressure,
$P_a =$ atmospheric pressure,
$a =$ tangent of the secant friction angle for an effective normal stress of one atmosphere, and
$b =$ empirical constant describing the curvature of the failure envelope.

The nonlinearity of the failure envelope is controlled by the parameter *b* and the inclination of the envelope by the parameter *a* in this equation. As *b* increases, the nonlinearity of the failure envelope decreases until *b* is qual to one and the envelope becomes linear. For linear envelopes, the parameter *a* is equal to tan ϕ', where ϕ' is the effective stress friction angle. Jiang et al. (2003) showed that *b* should be between 0.5 and 1.0 for the drained shear strength. Because of its simplicity and dimensionless parameters, this equation was used to develop the correlations presented in this research.

3.2 *Prudent Use of Correlations*

Correlations are powerful tools to obtain complex parameters, based on simple tests, to be used in engineering projects when time, money, or other constraints prevent formal measurement of such parameters.

Correlations provide a mean value based on a given dataset and a selected trendline. The accuracy of the parameters obtained from correlations depend on the quality of the data used to develop the correlation, the ability of the selected form of the equation for the trendline to accurately predict the observed behavior, and how well the data used to develop the correlation match the characteristics of the project.

Values obtained from correlations can be higher or lower than the actual value, if measured. For this reason, correlations should be used carefully and are more useful in preliminary analyses, as a check that measured values are in general agreement with the dataset used to develop the correlation, or to obtain a general form of the equation to develop local correlations.

The reliability of values obtained from correlations can be increased by using confidence limits. Confidence limits are obtained by offsetting the trendline using a multiplier of the standard deviation of the residuals. This offset can be done above or below the mean, depending on the parameter being estimated. For example, for shear strength parameters it is more conservative to use confidence limits below the mean while for compressibility, confidence limits above the mean are more conservative. The number of datapoints that fall above or below the confidence limits will depend on the number of standard deviations by which the limits are offset from the mean. Values obtained from confidence limits offset by one or two standard deviations will likely be too high or too low only 16% and 2% of the time, respectively. These percentages assume that the error in the correlation follows a normal or log-normal distribution. Another method to consider the uncertainty in the correlations is to perform formal reliability analyses for the specific project.

3.3 *Correlations*

Different correlations were developed to obtained fully softened and residual shear strength parameters based on index tests (e.g. liquid limit, plasticity index, clay-sized fraction). The correlations for fully softened shear strength parameters are presented in Figures 3 through 5 and for residual strength parameters in Figures 6 through 8. Included with these correlations are confidence limits to increase the reliability of the parameters obtained. Parameters that can be used to calculate shear strengths using Equation 1 are shown on the figures.

These correlations are recommended to be used for preliminary analysis or for final designs when parameters could not be obtained. For use in final designs, the uncertainty in the correlation needs to be considered by using a value below the mean, analyzing a range of expected values, or performing a formal reliability analysis. These correlations should only be used within the range of parameters used to develop them and no extrapolation is recommended.

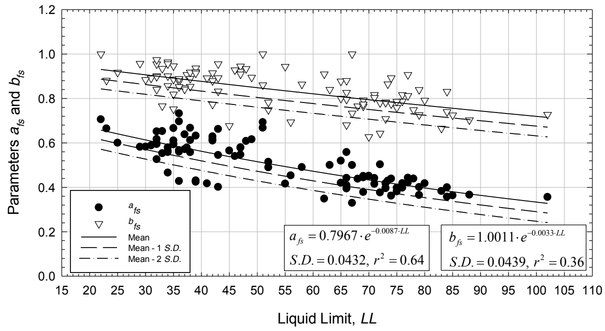

Figure 3. Correlation for fully softened shear strength parameters as a function of the liquid limit.

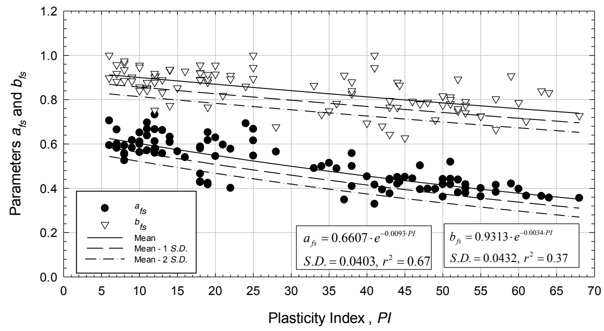

Figure 4. Correlation for fully softened shear strength parameters as a function of the plasticity index.

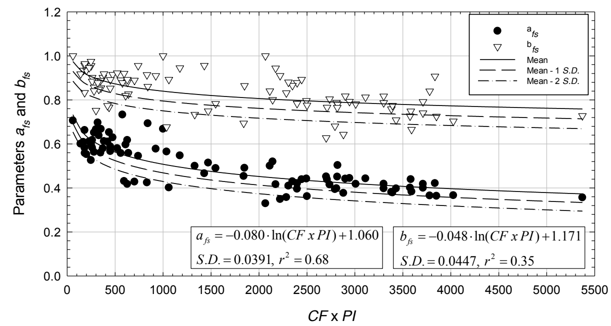

Figure 5. Correlation for fully softened shear strength parameters as a function of CF x PI.

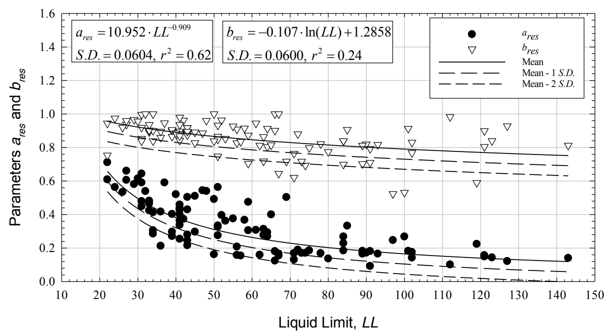

Figure 6. Correlation for residual shear strength parameters as a function of the liquid limit.

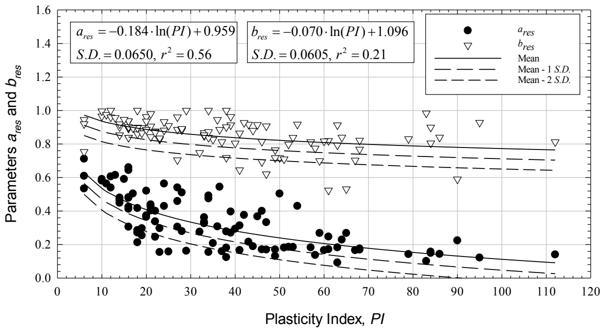

Figure 7. Correlation for residual shear strength parameters as a function of the plasticity index.

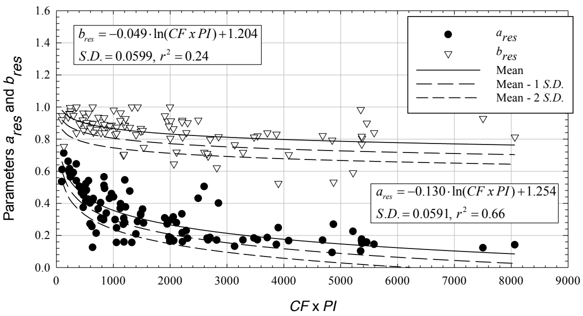

Figure 8. Correlation for residual shear strength parameters as a function of CF x PI.

3.4 *Statistical Assessment of the Correlations*

To perform formal reliability analyses and to assess the quality of the correlation it is necessary to have the statistical descriptors of the proposed equations. The complete forms of the proposed equations should include an error term with a mean a standard deviation as presented in Equations 2 through 13.

$$a_{fs} = 0.7967 \cdot e^{-0.0087 \cdot LL} + \xi_{a_{fs}}(\mu_{\varepsilon_{a_{fs}}}, \lambda_{\varepsilon_{a_{fs}}}) \tag{2}$$

$$b_{fs} = 1.0011 \cdot e^{-0.0033 \cdot LL} + \xi_{b_{fs}}(\mu_{\varepsilon_{b_{fs}}}, \lambda_{\varepsilon_{b_{fs}}}) \tag{3}$$

$$a_{fs} = 0.6607 \cdot e^{-0.0093 \cdot PI} + \xi_{a_{fs}}(\mu_{\varepsilon_{a_{fs}}}, \lambda_{\varepsilon_{a_{fs}}}) \tag{4}$$

$$b_{fs} = 0.9313 \cdot e^{-0.0034 \cdot PI} + \xi_{b_{fs}}(\mu_{\varepsilon_{b_{fs}}}, \lambda_{\varepsilon_{b_{fs}}}) \tag{5}$$

$$a_{fs} = -0.080 \cdot \ln(CF\ x\ PI) + 1.060 + \xi_{a_{fs}}(\mu_{\varepsilon_{a_{fs}}}, \lambda_{\varepsilon_{a_{fs}}}) \tag{6}$$

$$b_{fs} = -0.048 \cdot \ln(CF\ x\ PI) + 1.171 + \xi_{b_{fs}}(\mu_{\varepsilon_{b_{fs}}}, \lambda_{\varepsilon_{b_{fs}}}) \tag{7}$$

$$a_{res} = 10.952 \cdot LL^{-0.909} + \xi_{a_{res}}(\mu_{\varepsilon_{a_{res}}}, \lambda_{\varepsilon_{a_{res}}}) \tag{8}$$

$$b_{res} = -0.107 \cdot \ln(LL) + 1.2858 + \xi_{b_{res}}(\mu_{\varepsilon_{b_{res}}}, \lambda_{\varepsilon_{b_{res}}}) \tag{9}$$

$$a_{res} = -0.184 \cdot \ln(PI) + 0.959 + \xi_{a_{res}}(\mu_{\varepsilon_{a_{res}}}, \lambda_{\varepsilon_{a_{res}}}) \tag{10}$$

$$b_{res} = -0.070 \cdot \ln(PI) + 1.096 + \xi_{b_{res}}(\mu_{\varepsilon_{b_{res}}}, \lambda_{\varepsilon_{b_{res}}}) \tag{11}$$

$$a_{res} = -0.130 \cdot \ln(CF\ x\ PI) + 1.254 + \xi_{a_{res}}(\mu_{\varepsilon_{a_{res}}}, \lambda_{\varepsilon_{a_{res}}}) \tag{12}$$

$$b_{res} = -0.049 \cdot \ln(CF\ x\ PI) + 1.204 + \xi_{b_{res}}(\mu_{\varepsilon_{b_{res}}}, \lambda_{\varepsilon_{b_{res}}}) \tag{13}$$

In these equations, *a* and *b* are the shear strength parameters, the subscripts *fs* and *res* are used for fully softened and residual strength parameters, respectively, *LL* is the liquid limit, *PI* is the plasticity index, *CF* is the clay-sized fraction, ξ_a and ξ_b are the error terms for parameters a and b, μ_{ε_a} and μ_{ε_b} are the mean values of the error of the parameters a and b (which are approximately 0), and λ_{ε_a} and λ_{ε_b} are the standard deviation values presented in Table 1 with other statistical descriptors of the correlations. The covariance for the parameters a and b (COV(a, b)) is equal to 0.0037 and 0.0055, for the fully softened and residual conditions respectively. The correlation coefficient for a and b (δ(a, b)) is equal to 0.4223 and 0.3539, for the fully softened and residual conditions, respectively.

Table 1 Statistical descriptors of the proposed correlations and errors

Function	Std. Dev., $\lambda_{\varepsilon_a}, \lambda_{\varepsilon_b}$	r^2	COV (ξ_a, ξ_b)	$\delta\xi_a$, ξ_b
Equation 2	0.0432	0.64	0.00005	0.0284
Equation 3	0.0439	0.36		
Equation 4	0.0403	0.67	0.00013	0.0737
Equation 5	0.0432	0.37		
Equation 6	0.0391	0.68	0.00011	0.0619
Equation 7	0.0447	0.35		
Equation 8	0.0604	0.62	0.00012	0.0336
Equation 9	0.0600	0.24		
Equation 10	0.0650	0.56	0.00021	0.0535
Equation 11	0.0605	0.21		
Equation 12	0.0591	0.66	0.00029	0.0813
Equation 13	0.0599	0.24		

4 CONCLUSIONS

Six correlations to estimate the fully softened and residual shear strength using simpler index tests have been presented. These correlations are recommended to be used for preliminary designs and with some engineering judgement, can also be used for final design if direct measurements are not feasible in the project. These correlations should be used within the range of index properties of the soils used to develop them and extrapolation is not recommended.

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