

### Soil Characterization (Part 3) - Shear Strength Characterization for Slope Stability Analyses

#### Introduction

Shear strength is one of the most important factors in slope stability analyses, yet is also the most complex. Developing relevant and representative shear strength characterization of both the embankment and foundation soils for various loading conditions is a task that often gets muddled even by experienced engineers. This article endeavors to clarify some of the key considerations and methods used to develop shear strength parameters for slope stability analyses of embankment dams. Shear strengths can be measured through laboratory and field testing or estimated using empirical correlations. This article explains these methods for shear strength characterization of various soils under different loading conditions.

#### Previous Articles

The fundamentals of slope stability analyses were presented in the November 2013 issue of the *Western Dam Engineering* newsletter in an article titled "[Embankment Dam Slope Stability 101](#)," where the topic of shear strength characterization for slope stability analysis was introduced. Discussion was also provided on slope stability modeling for the following embankment loading conditions: **end-of-construction**, **steady-state drained**, **rapid drawdown**, and **seismic**.

The fundamentals of soil characterization for dams, including some introductory aspects of shear strength characterization, were presented in the July 2014 newsletter issue in an article titled "[Soil Characterization \(Part 1\) – Here's the Dirt](#)." That article presented a broad overview of properties pertinent to the overall performance and analysis of dams.

A subsequent article presented in the October 2014 newsletter issue titled "[Soil Characterization \(Part 2\) – Laboratory and Field Shear Strength Testing](#)" defined **shear strength**, **undrained and drained conditions**, and **total and effective stresses** and discussed various types of laboratory and field testing for evaluating the shear strength of cohesionless (sands and gravels) and cohesive (clays and silts) soils. This current article elaborates on utilizing laboratory and field testing

results for selection and development of shear strength parameters to be used in slope stability analyses for embankment dams.

You are invited to revisit and review the above three articles, as this article builds on many of the concepts presented in the previous articles.

#### What this Article Does Not Cover

This article focuses on shear strength characterization for various stability analyses. Considerations to determine what loading conditions should be analyzed, determining appropriate phreatic and pore pressure conditions, selecting critical cross sections, and the appropriate analysis methodology are outside the scope of this article. This article does not discuss shear strength characterization of rock or special soils such as cemented sands, highly sensitive ("quick") clays, and organic soils; the discussion is limited to the most common soils used in dam engineering and construction. This article also does not cover seismic shear strength characterization.

#### Typical Loading Conditions

Before developing shear strength parameters for use in slope stability analyses, it is important to understand the potential loading conditions by which an embankment dam should be evaluated. Shear strengths in embankment and foundation soils change throughout various loading conditions during the life of a dam. As a result, the stability of an embankment dam varies depending on the particular loading condition the dam experiences at a given time. Typical loading conditions include end-of-construction, steady-state drained, and rapid drawdown, and are discussed further below.

##### *End-of-Construction Loading Condition*

The end-of-construction loading condition evaluates the stability of an embankment dam during and at the end of construction. Construction may include the initial construction of a dam or additional construction resulting from dam modifications. This loading case often controls the design of new, or significant enlargements, of embankments; especially those founded on soft clays. This loading condition should be analyzed for embankment dams consisting of fine-grained (cohesive) embankment and/or foundation

soils that are expected to develop excess pore water pressures due to an increased load induced by construction. This case is also only applicable when undrained shear strengths are estimated to be less than drained shear strengths. Both upstream and downstream embankment slopes are evaluated under the end-of-construction loading condition. The most critical construction loading condition is typically at the end of construction; however, staged construction may require intermediate analyses.

For this loading condition, embankment and foundation soils are analyzed using either drained or undrained shear strengths depending on the permeability and saturation of the soil. Fine-grained soils generally have low permeability such that little drainage occurs during construction. Therefore, when saturated, these soils are assigned undrained (total stress) shear strengths. Laboratory tests used to measure undrained shear strengths of fine-grained soils include the unconfined compression (UC) test, unconsolidated-undrained (UU) triaxial test, consolidated-undrained (CU' or CU) triaxial test with or without pore pressure measurements, and direct simple shear (DSS) test. The shear strength envelope used should be consistent with the analysis method employed such that strengths are calculated based on confining pressure prior to construction.

Soils that are free-draining have relatively high permeability and are assigned drained (effective stress) shear strengths with the phreatic surface defined by groundwater conditions. Laboratory tests used to measure drained shear strengths of free-draining soils include the consolidated-drained (CD) triaxial test, CU' triaxial test, and direct shear (DS) test.

### ***Steady-State Drained Loading Condition***

The steady-state drained loading condition represents the long-term stability of the embankment dam under normal reservoir pool steady-state seepage conditions. Pore water pressures are assumed to have reached their steady-state condition with no excess pore water pressures remaining from construction or elevated reservoir pool levels. The phreatic surface and internal piezometric conditions correspond to long-term, normal operating conditions with the reservoir pool conservatively modeled at the maximum normal reservoir level, or service/principal spillway crest

elevation. Typically, only the downstream embankment slope is evaluated under the steady-state drained loading condition. The upstream embankment slope is generally not analyzed because of stabilizing water pressure on the upstream face, providing a buttressing effect on the embankment. However, the factor of safety can be low if the upstream slope is very steep. In this case, analysis of the upstream embankment slope may be warranted.

For this analysis, all embankment and foundation soils are assigned drained (effective stress) shear strengths. Laboratory tests used to measure drained shear strengths include the CD triaxial test, CU' triaxial test, and DS test.

### ***Rapid Drawdown Loading Condition***

This condition represents a rapid lowering of the reservoir from the steady-state, normal pool to a significantly lower elevation, removing the buttressing effect of the reservoir. During rapid drawdown of a reservoir, the rate of unloading on the upstream slope is typically assumed to occur instantaneously, such that pore water pressures within the embankment do not have time to dissipate in fine-grained (cohesive) soils. This analysis assumes the embankment soils below the normal pool phreatic surface are saturated to steady-state conditions prior to drawdown and will remain saturated after drawdown. Given adequate drainage and time, pore water pressures will eventually dissipate in the fine-grained embankment soils.

The rapid drawdown loading condition should be evaluated using a three-stage slope stability analysis as described by Duncan, Wright, and Brandon [2] for developing appropriate phreatic and shear strength parameters. The first stage of the analysis calculates the stress condition based on the existing steady-state seepage conditions of the embankment dam before drawdown. In the first stage, the phreatic surface and internal piezometric conditions correspond to long-term, normal operating conditions with the reservoir pool conservatively modeled at the maximum normal reservoir level, and all embankment and foundation soils are assigned drained (effective stress) shear strengths.

The second stage of the analysis calculates the stress condition immediately after drawdown. In this stage,

the phreatic surface is modeled at the lowest outlet elevation, and all soils that cannot drain as the reservoir is lowered are assigned undrained (total stress) shear strengths based on the effective stresses before drawdown, as calculated in the first stage. Coarser, free-draining soils having a permeability typically greater than  $10^{-3}$  centimeters per second are assigned drained shear strengths based on the effective stress after drawdown [2].

In the third stage of the analysis, the rapid drawdown stability factor of safety is calculated using the lower of either the first-stage undrained or second-stage drained shear strength. Rapid drawdown is one of the more complex stability analyses and the analyst should consult relevant references such as [2], [3], and [4] for further details.

The most common laboratory test used to measure shear strengths for the rapid drawdown loading condition is the CU' triaxial test, because this test can measure both undrained (total stress) and drained (effective stress) shear strengths. Other laboratory tests used to measure drained shear strengths include the CD triaxial test and DS test. Other laboratory tests used to measure undrained shear strengths include the UC test, UU triaxial test, CU triaxial test, and DSS test.

### Shear Strength Characterization

After the loading conditions for which an embankment dam should be analyzed are identified, appropriate shear strength parameters must be developed for the embankment and foundation soils under each applicable loading condition. Characterizing the shear strength of soils is dependent on both the type of soil and whether the soil behaves as undrained or drained under a particular loading condition. Provided below is a description of the shear strengths typically evaluated for coarse-grained, cohesionless soils (sands and gravels) and fine-grained, cohesive soils (clays and silts), including the corresponding laboratory and field testing to measure strengths and empirical correlations to estimate strengths.

#### Coarse-Grained Soils (Sands and Gravels)

Coarse-grained, or granular, soils (sands and gravels) are typically free-draining and defined by drained shear strengths, except for very rapid loading (e.g., seismic loading, which is not addressed in this article).

These soils are similar in strength characterization since they have high permeabilities and sufficient drainage capacity to prevent pore water pressures from changing under most loadings.

Characterizing the drained shear strength of coarse-grained soils involves evaluating or estimating the effective stress friction angle ( $\phi'$ ). The Mohr-Coulomb strength envelope for granular soils goes through the origin of stress, as illustrated in Figure 1, and thus the effective stress cohesion ( $c'$ ) is zero. Coarse-grained soils are therefore also often referred to as cohesionless soils. Although the effective stress cohesion is zero, the strength envelope for denser soils is often curved, as illustrated in Figure 1. For mathematical simplicity, an analyst may approximate the strength envelope as linear over the normal stress range of interest for the analysis, which may result in an "apparent" effective stress cohesion, as illustrated in Figure 2. It is important to understand that this is a mathematical convenience, and not a true property of the soil.

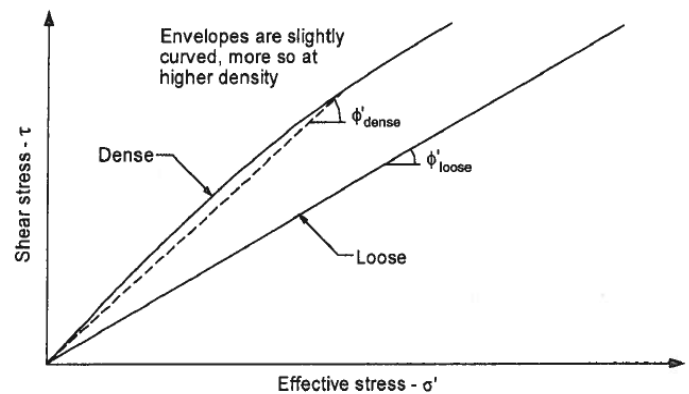


Figure 1: Mohr-Coulomb strength envelope for coarse-grained soils

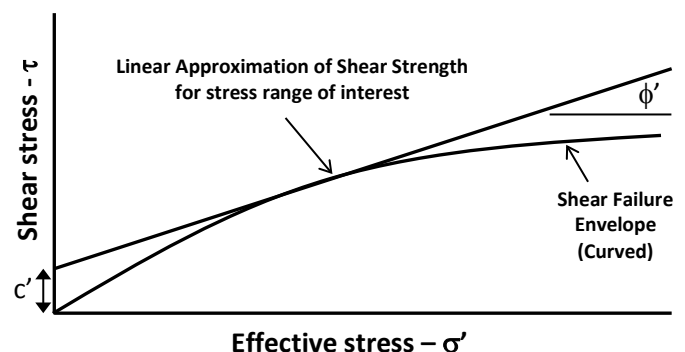


Figure 2: Curved shear strength envelope with linear interpretation and apparent cohesion,  $c'$

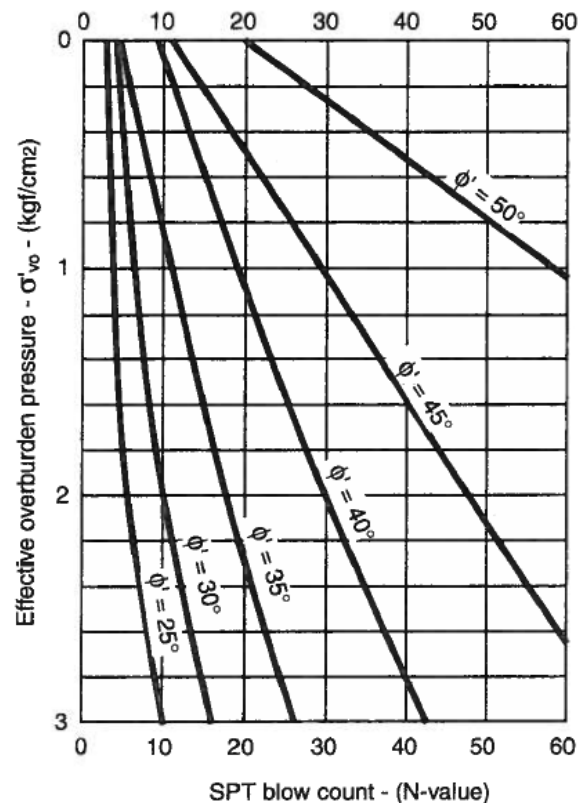
One can see that the lower the effective stress, as in low-height dams or shallow failure surfaces, the “apparent” cohesion intercepts should be very small. Using high cohesion in low-height dams is rarely justifiable, is very influential to the analysis results, and results in higher calculated factors of safety that are not defensible. A non-linear envelop may be more appropriate in these cases.

Typical factors affecting values of  $\phi'$  for coarse-grained soils include density, confining pressure, angularity, and gradation. Values of  $\phi'$  increase as density increases, confining pressures decrease, particle angularity increases, and the soil gradation becomes broader (a wider range of particle sizes are included).

Laboratory tests used to measure values of  $\phi'$  for coarse-grained soils include the CD or CU' triaxial shear test and the DS test (this test is best suited for finer-grained sands). It is difficult, however, to obtain undisturbed granular samples in the field or reconstitute the structure of natural deposits. Laboratory tests are often used to estimate  $\phi'$  for coarse-grained soils that will be placed during construction, such as embankment soils. Results from the laboratory tests should be checked against expected values based on gradation, relative density, and/or blow count in an effort to identify any obvious anomaly(ies). The presence of large particles (e.g., scalped samples or rockfill) may make laboratory test results misleading or impractical, and therefore not often warranted.

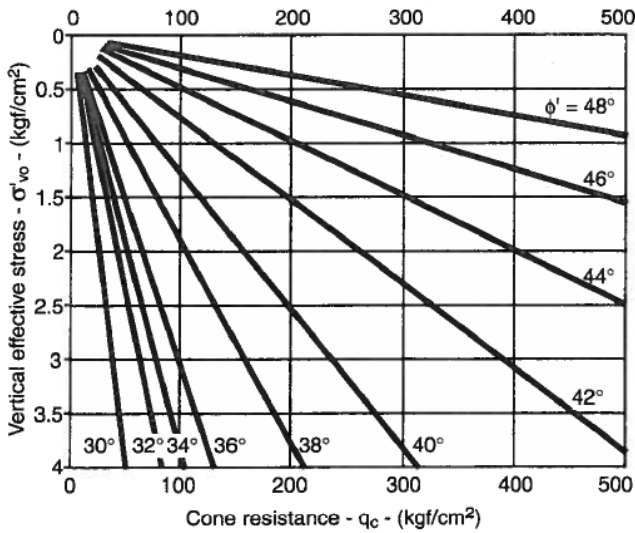
Results of field tests including the Standard Penetration Test (SPT), Cone Penetrometer Test (CPT), and shear wave velocity measurements are more commonly used to estimate values of  $\phi'$  for in-place, coarse-grained soils through the application of empirical correlations. Values of  $\phi'$  for in-place coarse-grained soils can also be estimated using empirical correlations to relative density and confining pressure, which are easier to measure directly than shear strength. A few of the more common strength correlations are presented below. These correlations, including others, are further described in reference [2], which is one of the more comprehensive references for shear strength characterization.

Figures 3 and 4 relate values of  $\phi'$  to overburden pressure and SPT blow count and CPT cone resistance, respectively. Relationships between  $\phi'$ , relative density, and SPT blow count or CPT cone resistance are summarized in Tables 1 and 2. While these tables are easy to use, they do not take into account the effect of confining pressure. Indirect correlations to relative density through SPT blow count or CPT cone resistance and overburden stress are shown in Figures 5 and 6.



Reference: Duncan, Wright, and Brandon (2014)

Figure 3: Relationship among SPT blow count, overburden pressure, and  $\phi'$  for sands



Reference: Duncan, Wright, and Brandon (2014)

Figure 4: Relationship between CPT cone resistance, overburden pressure, and  $\phi'$  for sands

Table 2: Correlation among Relative Density, CPT Cone Resistance, and Angle of Internal Friction for Clean Sands

State of packing	Relative density, $D_r$ (%)	$q_c$ (tons/ft <sup>2</sup> or kgf/cm <sup>2</sup> )	$\phi'$ (deg)
Very loose	< 20	< 20	< 32
Loose	20–40	20–50	32–35
Medium	40–60	50–150	35–38
Dense	60–80	150–250	38–41
Very dense	> 80	250–400	41–45

Source: Meyerhof (1976).

Reference: Duncan, Wright, and Brandon (2014)

Table 1: Relationship among Relative Density, SPT Blow Count, and Angle of Internal Friction for Clean Sands

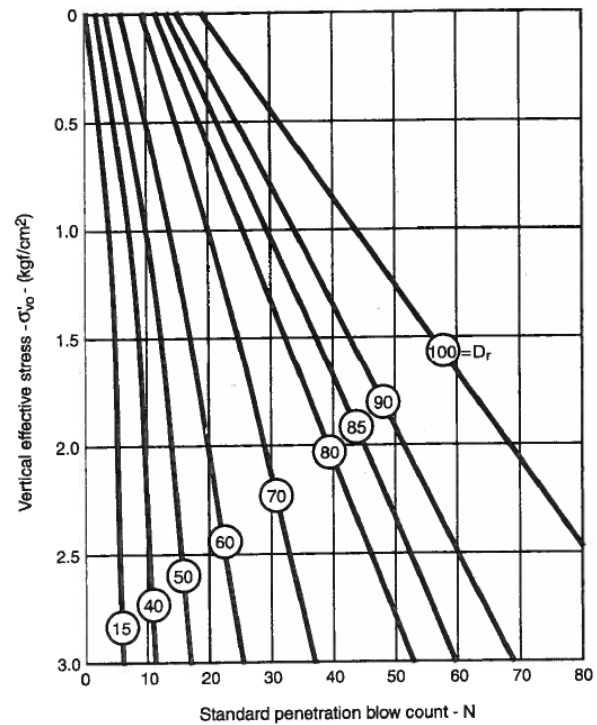
State of packing	Relative density, $D_r$ (%)	SPT blow count, $N^a$ (blows/ft)	Angle of internal friction $\phi'^b$ (deg)
Very loose	< 20	< 4	< 30
Loose	20–40	4–10	30–35
Compact	40–60	10–30	35–40
Dense	60–80	30–50	40–45
Very dense	> 80	> 50	> 45

Source: Meyerhof (1956).

<sup>a</sup> $N = 15 + (N' - 15)/2$  for  $N' > 15$  in saturated very fine or silty sand, where  $N$  is the blow count corrected for dynamic pore pressure effects during the SPT, and  $N'$  is the measured blow count.

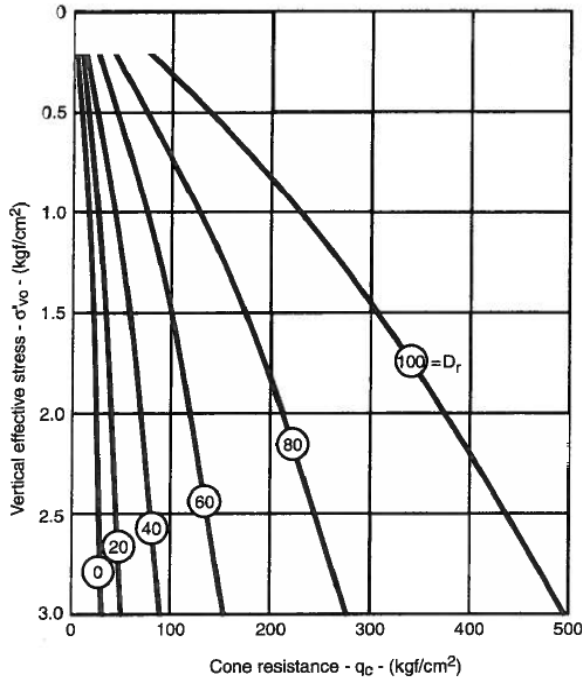
<sup>b</sup>Reduce  $\phi'$  by 5° for clayey sand; increase  $\phi'$  by 5° for gravelly sand.

Reference: Duncan, Wright, and Brandon (2014)



Reference: Duncan, Wright, and Brandon (2014)

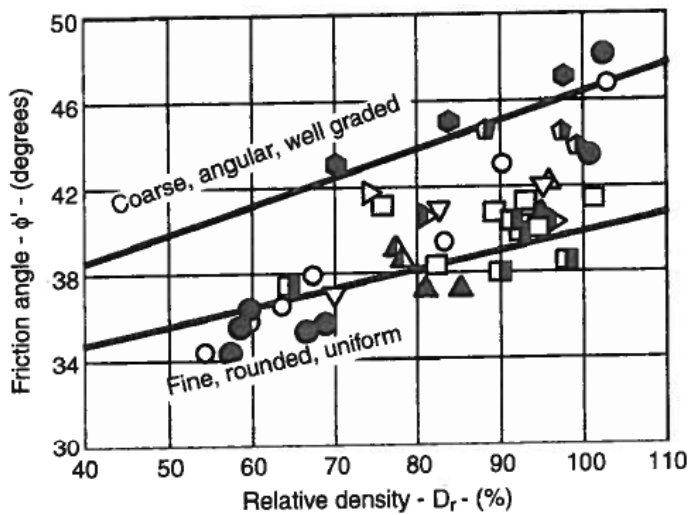
Figure 5: Relationship among SPT blow count, overburden pressure, and relative density for sands



Reference: Duncan, Wright, and Brandon (2014)

Figure 6: Relationship among CPT cone resistance, overburden pressure, and relative density for sands

The drained shear strength of coarse-grained soils is strongly affected by relative density. Values of  $\phi'$  corresponding to confining pressures of about 1 atmosphere are related to relative density for sands in Figure 7.



Reference: Duncan, Wright, and Brandon (2014)

Figure 7: Correlation between friction angle and relative density for sands

### Fine-Grained Soils (Clays and Silts)

Fine-grained soils (clays and silts) are generally defined by undrained shear strengths for short-term loading conditions and drained shear strengths for long-term loading conditions. These soils generally have low permeabilities and can develop excess pore water pressures during some static loading conditions. Given adequate drainage and time, pore water pressures will eventually dissipate in fine-grained soils.

#### Clays

Characterizations of shear strengths of clays are complex and the characterizations can be quite different for the different loading conditions, as discussed above. The drained shear strength of clays can be expressed in terms of effective stress ( $c'$ ,  $\phi'$ ) strength parameters. The undrained shear strength can be expressed in terms of total stress ( $c$ ,  $\phi$ ) strength parameters or in terms of undrained strength,  $S_u$ . Further, there are different forms of characterization that can be used for  $S_u$  – for example, constant  $S_u$ ,  $S_u$  as a function of effective confining stress, and  $S_u$  as a function of depth.

The overconsolidation ratio (OCR) of clays also has an impact on strength and is defined as the ratio of the maximum preconsolidation pressure of a soil mass to the current consolidation pressure the soil mass experiences. For normally consolidated to lightly overconsolidated clays, both undrained and drained shear strengths are of interest. When normally consolidated to lightly overconsolidated clays are loaded in shear, they tend to compress and generate positive pore water pressures, thereby resulting in an undrained shear strength that is generally less than the drained shear strength. Hence, the lower undrained shear strength must be used when analyzing undrained loading conditions. In contrast, for heavily overconsolidated, or compacted, clays, drained shear strengths are of most interest because these clays tend to expand when loaded in shear, and therefore, generate negative pore water pressures. The negative pore water pressures result in an undrained shear strength that is generally greater than the drained shear strength. As discussed previously with respect to rapid drawdown analyses, higher strengths resulting from negative pore water pressures are not normally

used in stability analyses because the negative pore water pressures cannot be relied upon in the field.

Typical drained Mohr-Coulomb failure envelopes for clays are presented in Figure 8. For normally consolidated clays, the Mohr-Coulomb strength envelope goes through the origin of stress and the effective stress cohesion ( $c'$ ) is equal to zero. For overconsolidated clays, the Mohr-Coulomb strength envelope is generally curved in the low stress range, but still goes through the origin such that the effective stress cohesion is equal to zero. Similar to coarse-grained soils, an analyst may approximate the strength envelope as linear over the normal stress range of interest for the analysis, which may result in an “apparent” effective stress cohesion. Again, strength envelopes with intercepts (shown in Figure 8) are a mathematical convenience.

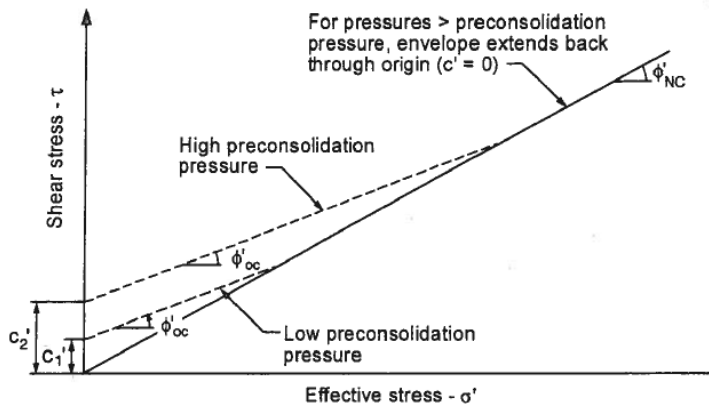
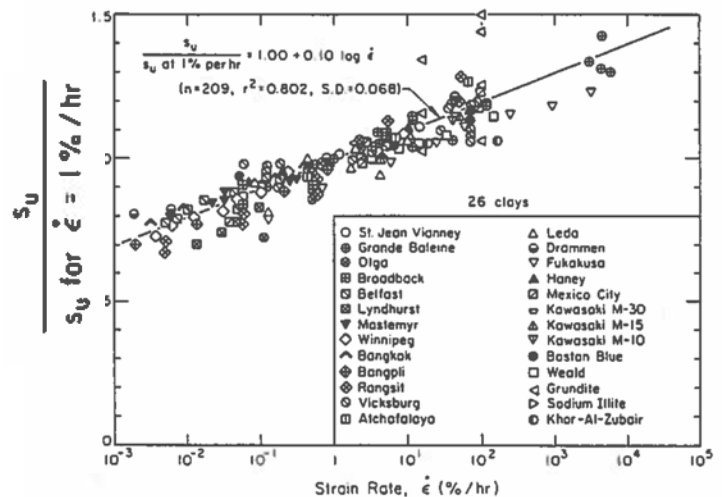


Figure 8: Mohr-Coulomb strength envelope for clays.

Stiff-fissured clays that are heavily overconsolidated should be carefully characterized. The undisturbed peak shear strength is generally not used to evaluate the stability of slopes composed of these soils. Shear strengths that can be mobilized in the field are generally less than in the laboratory since more softening and swelling occurs in these soils over long periods of time. Therefore, fully softened and/or residual shear strengths are generally more appropriate. If you are dealing with fissured clays, reference [2] should be consulted for its thorough discussion on that topic.

Other factors affecting clay strengths include anisotropy and strain rate. The undrained shear strength of clays varies with the orientation of the

principal stresses at failure and with the orientation of the failure plane. Isotropically consolidated soils generally yield higher shear strength than anisotropically consolidated soils where the vertical stress is higher than the horizontal. Common laboratory tests (i.e., CU) typically use isotropic consolidation, yet it should be recognized that soils in the field often exhibit anisotropic stress conditions. Furthermore, undrained shear strengths evaluated through laboratory testing can sometimes be overestimated due to the higher strain rates used to fail the specimen compared to those in the field. Figure 9 shows the undrained shear strength of saturated clay increases with increase in strain rate.



Reference: Mitchell and Soga (2005)  
Figure 9: Effect of strain rate on undrained shear strength of clay.

Laboratory tests used to measure the undrained shear strength ( $c$ ,  $\phi$  or  $S_u$ ) of clays include the UC test ( $S_u$ ); UU, CU, CU' triaxial shear test ( $c$ ,  $\phi$  or  $S_u$ ); and the DSS test ( $S_u$ ). Sample disturbance can reduce the undrained shear strength measured in laboratory tests. This effect may be reduced if the sample is consolidated to the same confining pressure it was consolidated to in the field. The SHANSEP (Stress History and Normalized Soil Engineering Properties) method can also compensate for sample disturbance and is a common approach used to estimate the undrained shear strength of clays. As described by Ladd and Foot (1974) and Ladd et al. (1977), the method involves consolidating clay samples to effective stresses that are greater than the in-situ stresses and interpreting

measured strengths in terms of an undrained shear strength ratio,  $S_u/\sigma'_v$ . Shear strength ratios increase with higher OCRs; meaning overconsolidated clays have higher shear strength than normally consolidated. See reference [2] for further discussion.

A field test used for direct measurement of the undrained shear strength ( $S_u$ ) of clays is the vane shear test, which has been successfully used for measuring the undrained shear strength of soft to medium stiff clays. Limitations are that the test can be affected by sand lenses and seams and the raw undrained shear strength measured from the test requires an empirical correction factor that varies with plasticity index and accounts for anisotropy and strain rate effects. The data on which the correction factor is based are widely scattered and therefore vane strengths should not be viewed as precise. The pocket penetrometer test and torvane test can be used to obtain very quick, approximate measurements of undrained shear strength in the field or laboratory. However, the pocket penetrometer and torvane tests are relatively crude and should be considered as only rough indications of shear strength.

The laboratory test most commonly used to measure the drained shear strength ( $c'$ ,  $\phi'$ ) of clays is the CU' triaxial shear test. The CU' test is more practical than the CD test because the strain rates required for a CD test are typically extremely slow, requiring an impractically long test time. In addition, the CU' test can be used to obtain both undrained (total stress) and drained (effective stress) shear strength parameters. However, the CD triaxial test and DS test can also be used, if the long test times can be accommodated. For stiff-fissured clays, laboratory tests are performed on remolded specimens to evaluate fully softened and/or residual drained shear strengths. The DS test is commonly used to measure the fully softened shear strength of stiff-fissured clays. Torsional ring shear tests are most suitable for estimating the residual shear strength of stiff-fissured clays since the test can measure shear stresses over any magnitude of displacement through continuous rotation.

Laboratory tests provide the best strength data for clays, and reasonably undisturbed samples of these materials can typically be obtained. However, various empirical correlations developed to estimate strengths

for clays may be sufficient in some cases. It is recommended these methods and correlations be used with caution, since the behavior, and hence strength characterization, for clays is typically more complex than for granular soils. A few of the more common shear strength correlations are presented below. These correlations, and others, are further described in reference [2]. It may also be useful to use these correlations as a check to validate the results of laboratory tests.

Results of field tests including the SPT, CPT, and shear wave velocity measurements can be used for estimating the undrained shear strength ( $S_u$ ) of clays through the application of empirical correlations. SPT blow counts ( $N$ ) in clay can be used to roughly estimate the variation of  $S_u/N$  with plasticity index, as shown in Figure 10.  $S_u$  can also be estimated from CPT cone resistance using the following relationship:

$$S_u = \frac{q_c - \sigma_{vo}}{N_k^*}$$

Where:  $q_c$  = cone tip resistance,  $\sigma_{vo}$  = total overburden pressure at test depth,  $N_k^*$  = cone factor

The variation of  $N_k^*$  with plasticity index for a variety of clays is shown in Figure 11. An  $N_k^*$  value of 14 is typically applied to clays for any value of plasticity index.

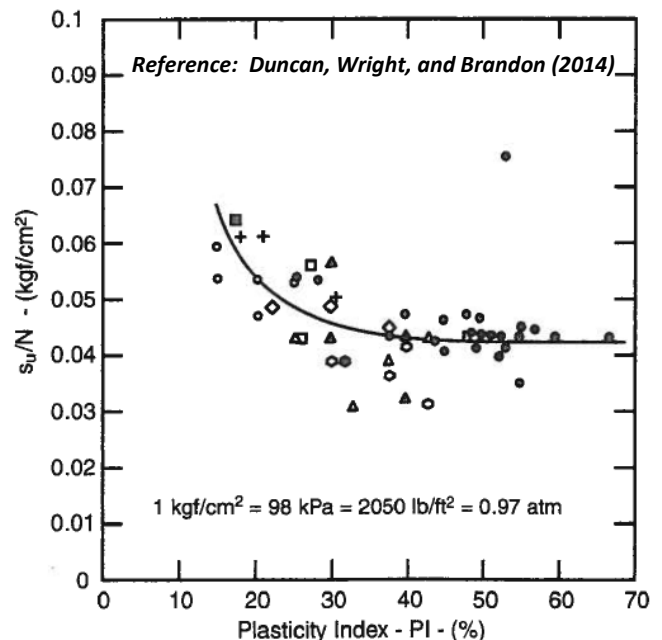
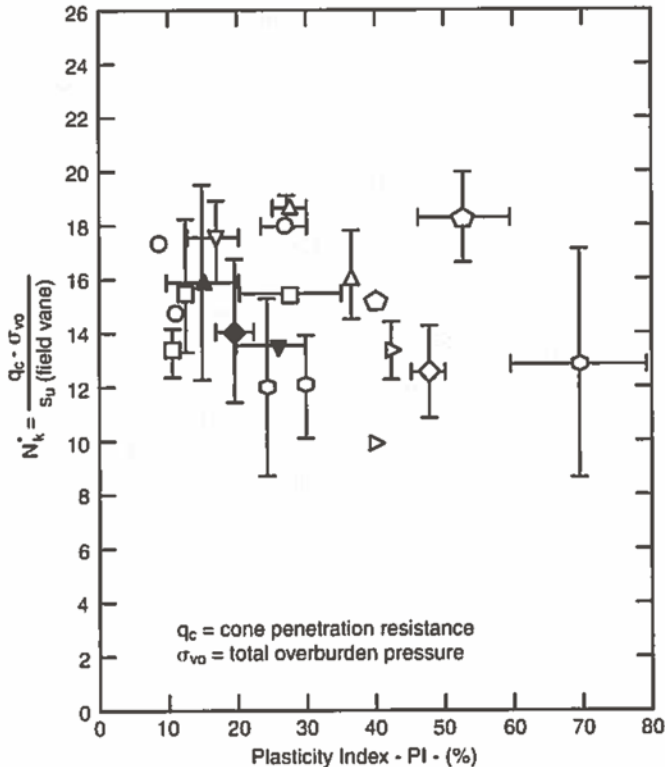


Figure 10: Variation of the ratio of undrained shear strength ( $S_u$ ) divided by SPT blow count



Reference: Duncan, Wright, and Brandon (2014)

Figure 11: Variation of the cone factor ( $N_k$ ) with plasticity index for clays

Drained shear strength parameters ( $c'$ ,  $\phi'$ ) for clays vary depending on consolidation of the clay. As shown previously in Figure 8, the Mohr-Coulomb strength envelope for normally consolidated clays goes through the origin of stress and the effective stress cohesion ( $c'$ ) is equal to zero. Typical values of peak effective stress friction angle ( $\phi'$ ) for normally consolidated clays are provided in Table 3. For overconsolidated clays, the Mohr-Coulomb strength envelope is generally curved in the low stress range and approximated as linear over the normal stress range of interest for the analysis, which may result in an “apparent” effective stress cohesion ( $c'$ ). Typical peak values of  $\phi'$  and  $c'$  for compacted clays corresponding to a relative compaction of 100 percent of the Standard Proctor maximum dry density are given in Table 4.

Table 3: Typical Values of Peak Friction Angle ( $\phi'$ ) for Normally Consolidated Clays<sup>a</sup>

Plasticity index	$\phi'$ (deg)
10	33 ± 5
20	31 ± 5
30	29 ± 5
40	27 ± 5
60	24 ± 5
80	22 ± 5

Source: Data from Bjerrum and Simons (1960).

<sup>a</sup> $c' = 0$  for these materials.

Reference: Duncan, Wright, and Brandon (2014)

Table 4: Typical Peak Drained Strengths for Compacted Cohesive Soils

Unified classification	Relative compaction, RC <sup>a</sup> (%)	Effective stress cohesion, $c'$ (kPa)	Effective stress friction angle, $\phi'$ (deg)
SM-SC	100	15	33
SC	100	12	31
ML	100	9	32
CL-ML	100	23	32
CL	100	14	28
MH	100	21	25
CH	100	12	19

Source: After U.S. Dept. Interior (1973).

<sup>a</sup>RC, relative compaction by USBR standard method, same energy as the Standard Proctor compaction test.

Reference: Duncan, Wright, and Brandon (2014)

### Silts

Silts have an interesting soil particle composition, as they can behave similarly to either fine sands or clays. When the term fine-grained is used, it almost always includes silts in this category. But silts themselves can be divided into two general categories, non-plastic and plastic. Non-plastic silts behave more like fine sands, while plastic silts behave more like clays. Evaluating whether a unit of silt is non-plastic or plastic can be achieved using the Atterberg Limit laboratory test (refer to “[Soil Characterization \(Part 1\) – Here’s the Dirt](#)”).

Since silts can have a wide range of permeabilities, it can be difficult to predict if these soils will behave as drained or undrained under various loading conditions.

It is common to characterize silts using both drained and undrained shear strengths similar to clays. For drained conditions, the shear strength of silt can be characterized by an effective stress friction angle ( $\phi'$ ) with an assumed effective stress cohesion ( $c'$ ) equal to zero. For undrained conditions, the shear strength of silts can be expressed using total stress strength parameters ( $c$ ,  $\phi$ ) or in terms of undrained strength,  $S_u$ . Similar to clays, there are different forms of characterization that can be used for  $S_u$  – for example, constant  $S_u$ ,  $S_u$  as a function of effective confining stress, and  $S_u$  as a function of depth.

Laboratory tests used to measure values of  $\phi'$  for silts include the CD or CU' triaxial shear test and the DS test. Laboratory tests used to measure the undrained shear strength ( $c$ ,  $\phi$  or  $S_u$ ) of silts include the UC test ( $S_u$ ), UU or CU/CU' triaxial shear test ( $c$ ,  $\phi$  or  $S_u$ ), or the DSS test ( $S_u$ ). Similar to coarse-grained soils, it can be difficult to obtain quality undisturbed samples of silts in the field, particularly non-plastic or very low plasticity silts.

Strength behaviors of silts have not been as widely studied as those of sands or clays. As a result of this general lack of research and compilation of data, very few empirical correlations exist for predicting shear strength values for silts. Empirical strength correlations that are available for silts are often regionally specific and developed with relatively limited data sets. Similar to sands and clays, SPT, CPT, and shear wave field tests can be used for empirical strength correlations of silts. Empirical correlations using results of field tests for sands can generally be applied to estimate shear strengths of non-plastic silts. Shear strengths of plastic silts can generally be estimated from empirical correlations using results of field tests for clays. It would be prudent to incorporate a level of conservatism when using correlations for silts.

### Shear Strengths by Federal Agency

Various government agencies have identified shear strength envelopes to be used for design loading conditions. Therefore, stability analyses performed for these agencies should utilize their specific strength characterization criteria. Reference [1] provides a useful summary of then current guidance provided by various federal agencies such as: United States Army Corps of Engineers; Bureau of Reclamation; United

States Department of Agriculture, National Resources Conservation Service; and Federal Energy Regulatory Commission. Guidance documents for each agency should be referenced for any updates.

### Conclusion

Slope stability analyses of embankment dams are highly dependent on shear strength parameters assigned to the embankment and foundation soils. It is therefore very important to perform a detailed shear strength characterization of the various soils to obtain meaningful slope stability results. Shear strength characterization requires both knowledge and experience to select and develop appropriate parameters for various embankment and foundation soils. Shear strengths of soils vary depending on the loading conditions needing to be analyzed, and the variations have a significant impact on slope stability calculations. Careful shear strength characterization is therefore an imperative, in most cases the most important, component of slope stability analyses for embankment dams.

### Useful References

- [1] [Strength of Materials for Embankment Dams, United States Society on Dams, February 2007.](#)
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