Fully Softened Strength of Natural and Compacted Clays for Slope Stability

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ABSTRACT: The findings of a workshop on the use of fully softened shear strength (FSS) for stability of slopes in highly plastic clays are summarized and discussed. Held at Virginia Tech on August 16 and 17, 2011, the workshop included 57 engineers and geologists from academia, private consulting practice, and government agencies. Four major themes were considered by breakout groups: (1) the softening process, (2) techniques for measuring or estimating FSS, (3) use of FSS in stability analyses, and (4) research needs for FSS. The softening process working group examined the mechanism of softening, the types of clays that experience softening, and the depth and extent of softening. The laboratory measurement working group discussed types of equipment appropriate for measuring FSS, sample preparation techniques, appropriate methods of representing FSS, and the use of FSS correlations. Discussion on the use of FSS covered a wide range of topics, including guidelines for use of FSS, the use of curved strength envelopes, and the application of FSS to various types of slopes. The research needs identified included necessary updates to USACE engineering manuals, pore pressures appropriate for use with FSS, needed improvements in laboratory measurement of FSS, and the investigation and cataloguing of case histories of FSS slope failures.

BACKGROUND – PREVIOUS WORK AND CURRENT UNDERSTANDING

Terzaghi (1936) first recognized that the strength of stiff fissured clays that can be mobilized around excavations is considerably smaller than the strengths of these clays measured in laboratory tests on undisturbed samples. He attributed lower field strengths to swelling of clay along fissures within the clay mass due to lateral stress relief. Henkel (1957) analyzed four excavated slope failures in stiff fissured London clay and found that values of the effective stress cohesion intercept, c’ calculated by back analysis of slope failures were smaller than those measured in laboratory tests, and that these values of c’ decreased with the length of time between excavation and failure.

Studying failures of a number of slopes in the UK, Skempton (1964) observed a decrease of the shear strength around excavations in the heavily fissured and jointed London clay. In 1970, Skempton made an empirical conclusion that softening over time brings clay to the "critical state" where further shear distortion will not result in any change in water content. Approximating the critical state strength with the drained normally consolidated strength, Skempton conservatively suggested that "we may say that the fully softened strength parameters c' and ϕ' are equal numerically to the peak strength parameters of the normally consolidated clay." In later analyses of London clay, Chandler and Skempton (1974) and Skempton (1977) pointed out that, although c' is close to zero in the fully softened condition, it is excessively conservative to ignore the small values of c' observed in test data interpreted with linear strength envelopes, because of the significant effect of these small values of c' on shallow slides.

The work of Skempton and others can be summarized using three categories of drained strength for clays as illustrated by the stress-displacement curves in Figure 1: 1) the peak strength mobilized in undisturbed test specimens from naturally occurring clays, or from compacted clay fills, 2) fully softened strength as the end result of the softening process and the associated increase in void ratio, and 3) the residual strength mobilized after large shear displacements have aligned the plate-shaped clay particles.

Throughout this paper, the term "fully softened strength" implies the strength envelope, rather than a discrete value of strength. In most instances using "strength" to imply "strength envelope," causes no confusion.

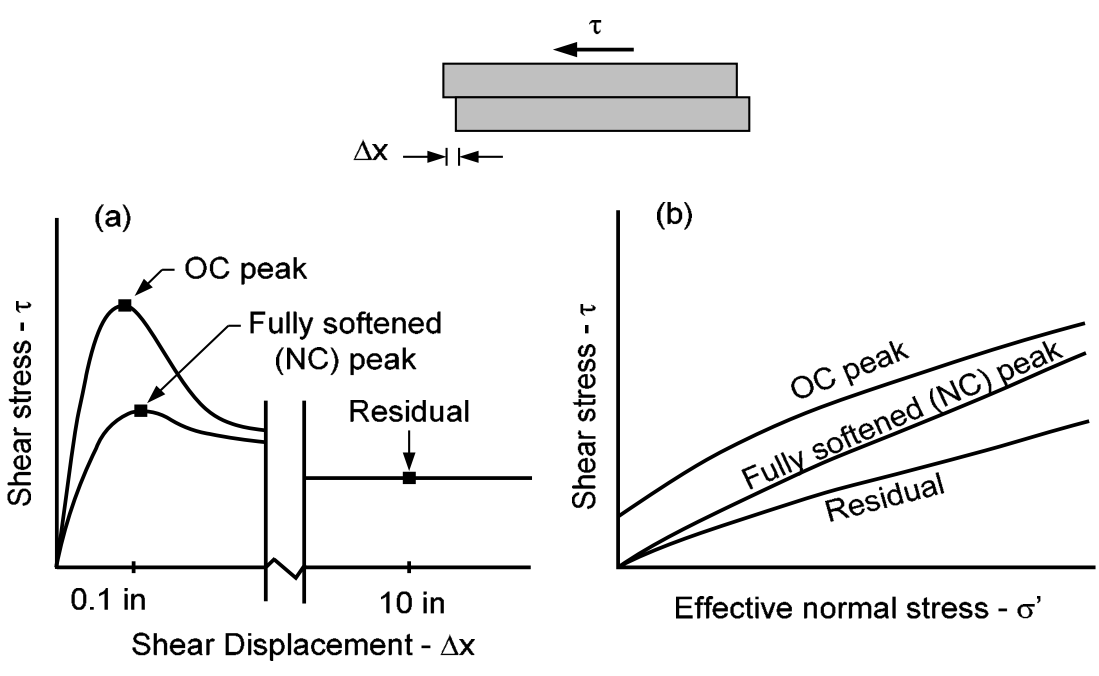

Figure 1 (a) Stress-displacement curves for overconsolidated and fully softened (normally consolidated) natural stiff fissured clays, and (b) overconsolidated peak, fully softened peak and residual strength envelopes.

In 1984, Steve Wright and his colleagues began studies of shallow slope failures in embankments of the highly plastic Paris and Beaumont clays in Texas (Staufer and Wright 1984; Green and Wright 1986; Rogers and Wright 1986; and Kayyal and Wright 1991). Triaxial specimens were subjected to cycles of drying and wetting in the laboratory. The consequent softening reduced the drained strength of these clays nearly to the normally consolidated strength. These reduced strengths matched well with back analysis of the observed failures, provided the piezometric surface at the time of the slide was assumed to have been at the surface of the slope. Their studies suggest that softening of compacted clay embankments results from formation of shrinkage cracks during periods of drought, followed by water entering these cracks during wet periods, softening the clay. Wright and his colleagues recommended that long-term strengths for embankments of compacted highly plastic clay can be measured using strength tests on remolded normally consolidated test specimens. Day and Axten (1990) and McCook (1997) also studied shallow failures in clay embankments and also found that strengths below peak were appropriate for design.

Stark, Choi, and McCone (2005) presented ring shear tests on normally consolidated clays with Liquid Limits varying from 20 to 290, at normal stresses from 50 kPa to 400 kPa. They developed correlations between Liquid Limit, clay size fraction, and fully softened secant friction angle. The secant friction angles are stress dependent and correspond to curved, rather than linear, shear strength envelopes. Additional fully softened direct shear testing and correlations have been performed recently by Tiwari and Ajmera (2011).

The *Workshop on Shear Strength for Stability of Slopes in Highly Plastic Clays* (Duncan et al. 2011) was held in August 2011 at Virginia Tech to examine how knowledge regarding FSS has been incorporated in geotechnical engineering practice, and what further studies are needed in this area. The workshop brought together 57 engineers and geologists from academia, private consulting practice, and government agencies. Their names and a photo are included in the appendix. Discussions during the workshop focused on (1) the mechanisms of the softening process, (2) laboratory measurement of fully softened strength, (3) use of fully softened strength for slope stability analysis, and (4) future research needs. These same topics provide the general framework for this paper. The following sections describe the consensus of the workshop participants where consensus was reached, and the range of opinion where consensus was not reached.

THE SOFTENING PROCESS

The workshop participants generally agreed regarding the mechanisms that lead to softening. The two principal mechanisms of softening are 1) softening around excavations as first described by Terzaghi (1936) and 2) softening of compacted fills due to desiccation and formation of shrinkage cracks. Lateral stress relief caused by excavation or desiccation allows water to infiltrate the clay mass and the clay to swell. In the process, negative pore pressures dissipate, and the clay becomes weaker. These changes in stress and the resulting strains can lead to development of additional cracks and repetition of the softening process. Degradation by leaching of salts and changes in mineralogy were also suggested as mechanisms that can lead to reduction in shear strength, and in this sense might be included as mechanisms of softening.

While softening can occur in clays of lower plasticity, it is most pronounced in highly plastic clays. Index properties, such as Liquid Limit or Plastic Limit, are an important factor in determining which clays soften and how much; however local experience, mineralogy, and climate also play a role. In general the likelihood of reaching the fully softened condition probably increases with

- higher Plasticity Index,
- existence of fissures or shrinkage cracks within the mass,
- water contents much above the shrinkage limit,
- higher clay size fractions,
- lower silt and sand content, and
- higher activity (ratio of PI divided by percent finer than two microns).

The depth to which softening extends depends on the controlling mechanism. For example, the depth of an excavation will determine the extent of significant lateral stress reduction, which in turn governs the depth to which cracks will open, admitting water leading to softening. For excavation slides in London brown clay, Skempton (1977) reported slide depths as great as 11.5 meters (measured normal to the slope surface) with average effective normal stresses on the failure surface up to 50 kPa. In the case of softening in clay embankments, the depth of softening is likely dependent on the depth of desiccation cracking, which is governed by soil properties and climate. In most cases the depth of softening and slides has been found to be two meters or less, with examples cited as deep as four meters.

Softening can take significantly different amounts of time to develop, depending on the magnitude of stress changes, the nature of the soils involved, and the climate. The time required to reach FSS might be as little as ten years in some cases, and as long as 60 years in others. Although slides may occur in shorter periods of time on steep slopes with higher shear stresses, the shear strength at failure is probably greater than the FSS.

Experiences with softening will vary from one geographic region to another. Firm understanding of the principles that govern softening should supersede the use of rules of thumb developed in regions with different soil or climatological conditions.

MEASURING OR ESTIMATING FULLY SOFTENED STRENGTH

Fully softened shear strength has been measured by direct shear, triaxial, and ring shear tests. Standardized procedures have been developed for fully softened ring shear testing (ASTM D7608) and are under development for fully softened direct shear testing. The advantages and disadvantages of each type of test are summarized in Table 1. The general consensus was that the fully softened shear strength is best measured with the direct shear apparatus. The differences in values of FSS parameters measured using different types of tests need to be more fully investigated.

The procedures recommended by the testing work group primarily focused on ring shear or direct shear equipment. The use of ball mills or blenders may not be necessary for all FSS testing. Test specimens should be reconstituted using project-specific water or deionized/demineralized water. Project-specific water can be used when deemed appropriate. Water should be added to the soil as necessary to increase the as-delivered water content until the soil can be pushed through a No. 40 sieve. After sieving, more water should be added to the soil until the water content is near the Liquid Limit. The test soils should be allowed to fully hydrate for a minimum of 48 hours prior to forming the sample. The specific method that the sample is formed, whether by pastry bag, spatula, or other means, should be left up to the discretion of the individual laboratory.

Table 1 Advantages and disadvantages of apparatuses used to measure FSS.

	Direct Shear	Ring Shear	Triaxial
Advantages	Common Most available Easiest to perform Easiest to interpret data	ASTM standard available Short consolidation time Small amount of soil needed	Common
Disadvantages	One to two weeks required per point No current standard Soil can extrude from the top Top cap can tilt Stress concentrations	Difficult to run test slow enough for fat clays Rare Thin sample after consolidation Expensive	Much time required Soft soils are difficult to form into test specimens Difficult to conduct tests at low stresses

The variation of FSS with increasing normal stress is non-linear. Figure 2 shows an example of this curvature. Because of this curved shape, four or five data points should be obtained to define an envelope, as opposed to the three data points commonly used in traditional ring shear and direct shear testing. The additional data points should be used to better define the strength envelope at low effective normal stresses, preferably below 25 kPa. The FSS is generally reached at relatively low displacements (<0.5 cm), and should be considered as the peak of the stress–displacement curve. For ring shear and direct shear tests, the vertical displacement should be recorded and examined as well. At zero normal stress, the strength envelope should pass through the origin of the normal stress–shear stress plot. If the envelope does not pass through the origin, then potential testing problems should be investigated. The power function representation, suggested by Lade (2010), is useful in representing the curved strength envelope. In order to use a curved envelope for limit equilibrium analysis, the software must allow the user to define shear strength using either a power function or a finely-divided piecewise linear relationship.

Correlations between FSS and index properties, particularly the one developed by Stark et al. (2005), are valuable tools when a project is in the conceptual stage, but should not replace laboratory testing. Unpublished FSS data from United States Army Corps of Engineers (USACE) projects presented at the workshop suggests that such correlations can provide useful insight into the validity and application of laboratory test results. Agencies should make their data available to researchers to continually update current correlations.

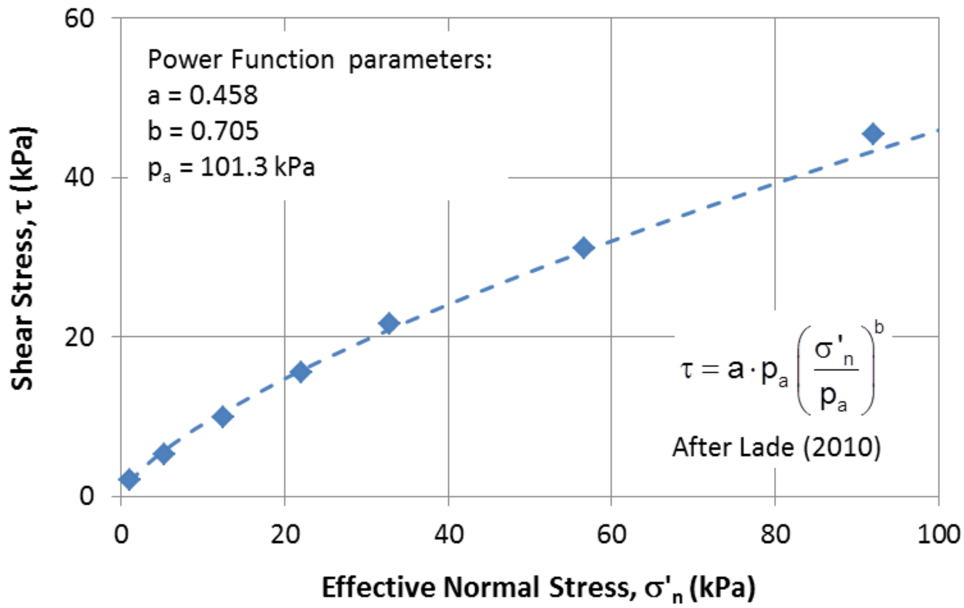

Figure 2 Curved envelope for FSS of Paris Clay (after Kayyal and Wright 1991)

USE OF FULLY SOFTENED STRENGTH IN STABILITY ANALYSES

Skempton (1970) stated that fully softened strength is applicable to "first-time slides in stiff fissured clays." Although this was an empirical observation based on back analyses of slides in London clay, it seems logical that it applies also to excavated slopes in other clays with similar characteristics (LL, PI, OCR). Studies by Wright and others have similarly shown that fully softened strength is appropriate for analyses of potential sliding at relatively shallow depths within embankment slopes in highly plastic clays in climates where extensive wetting and drying occurs. Engineering judgment must be used to decide how broadly these principles apply and to what depth softening will occur in particular cases.

The use of fully softened strength in slope stability studies is a means of allowing for gradual loss of strength over time due to development of fractures and desiccated zones. This loss of strength is not reflected in peak strengths measured by site investigations or laboratory testing prior to construction. Nor is it reflected by the peak strength of compacted laboratory specimens of clay measured after saturation. Fully softened strength simply, but appropriately, accounts for effects that occur over time, such as weathering, dissipation of negative pore pressures, and development of desiccated and cracked zones. It is important to remember that the use of fully softened strength for slope stability studies is based on experience and back analyses of slope failures. Applying the fully softened strength concept appropriately requires high quality geologic studies, high quality site investigations, high quality laboratory tests, evaluation of past performance, and good engineering judgment. These are essential components of all effective evaluations of slope stability, whether fully softened strengths are appropriate or not. The assumed depth of softening for embankment fill necessarily involves engineering judgment based on knowledge of soil mineralogy (typically inferred from index testing), experience with the site conditions, and consideration of climate. In some cases, regulatory restrictions may also influence engineering decisions regarding the depth of softening. More post-failure explorations should be performed to determine the depth of softening for case studies.

Satisfactory geotechnical engineering for slopes cannot be achieved without experience and use of judgment. An important aspect of this judgment is evaluating the interaction between shear strength, factor of safety, and consequences of failure for any given project. These cannot be separated from each other. Judgment is also needed to achieve a high quality sampling and testing program. Data from the wrong type of test, or from poorly performed tests, provide nothing of value for a project. The following guidance regarding the use of FSS is not intended to supplant engineering judgment or to limit flexibility in application.

Curved Strength Envelopes

Strength envelopes for many soils, including those for fully softened strength, are curved, as shown in Figure 2. However, the application of curved envelopes in practice has often lagged in favor of "equivalent linear" or piece-wise linear envelopes. Linear envelopes with no effective cohesion coincide with our understanding of normally consolidated clay behavior but tend to underestimate strength for shallow slides. When an effective stress cohesion intercept is used, linear envelopes usually over-predict strength at low normal stresses.

The position of the critical slip surface in a limit equilibrium stability analysis is influenced by the type of strength envelope used. With a curved strength representation, the critical slip surface will not extend as deep as in an analysis with a large cohesion. On the other hand, the curved nature of the envelope will generally prevent the analyses from degenerating to a zero-depth infinite slope failure mechanism. The relative position of the critical slip surface expected for a curved envelope is compared to other common strength models in Figure 3. Further studies will be needed to determine if depths of sliding predicted by curved strength envelopes are consistent with actual sliding depths, or if actual sliding depths are controlled by limited depths of softening, or both.

Soil around Excavations

Nearly everyone agreed that FSS is applicable to shallow depths of at least two to three meters below the surface of permanent excavations in fissured clays, and most thought that softening could extend considerably deeper in this case. More study is required to define the limits to which softening can extend around excavations. The depth of softening for excavated slopes appears to be a function of many factors, including slope geometry, soil stress history, and soil composition. The influence of these factors on the depth of softening in excavations has not been thoroughly investigated and requires further research.

Few case studies of failures of excavated slopes involving FSS have been published since the work of Skempton and his colleagues. The workshop participants felt that, as a profession, we need to do a better job of documenting and reporting on case histories. This would reduce the amount of conjecture with respect to the depth to which fully softened strengths should be used for excavated slopes.

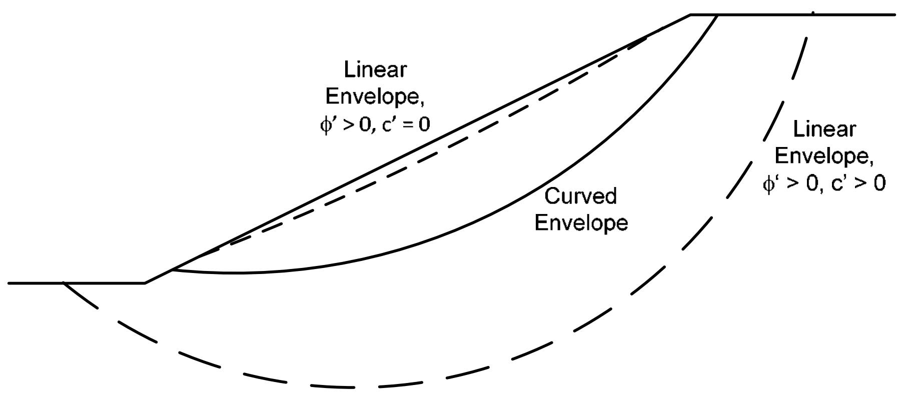

Figure 3 Relative positions of critical failure surfaces associated with different strength representations.

Embankments

The workshop participants possessed a wide range of opinion regarding the application of FSS to embankments. Many felt that FSS is applicable only to the upper two to three meters of embankments constructed of highly plastic clay, while a few thought that FSS parameters should be used throughout an embankment cross section.

Based on the case studies presented at the workshop, FSS failures in embankments tend to be shallow. No published case studies of deep seated slides due solely to softening of embankment fill are known. The best means of estimating the likely depth of softening for new embankments is through examination of local experience, because the depth depends on climate as well as soil type. When the stability of existing embankments is being evaluated, field exploration and laboratory testing of undisturbed samples can be relied on to determine the depth of softening.

Legacy levees represent a special problem where old embankments are encapsulated within new embankment fill as the levee is raised. The old levees may already be weakened by earlier softening or by earlier desiccation cracks that made them more vulnerable to softening. Thorough site exploration should identify this condition, and high quality, conventional laboratory tests should be sufficient to characterize softened zones buried in old embankments.

Compacted clay fills often behave more like intact (non-fissured) materials because of the lack of joints and fissures. Compacted clay fill may also contain significantly more sand and gravel than the natural soils for which the FSS concept was originally developed. The coarse fraction may impact the strength characteristics of the clay. In some locales, compacted clay slopes that are regularly irrigated and do not undergo the same degree of cyclic wetting and drying as highway embankments. It was suggested that irrigated slopes that are not subject to extensive desiccation are not as prone to desiccation cracking as are those that are subject to extreme climatological variation. Because of factors like these and the limited body of research available, FSS should not be applied indiscriminately to all compacted clay fills. More research into the use of FSS for compacted clays would be useful.

Embankment foundations

The possibility of softening in embankment foundations was also vigorously discussed during the workshop. While a few participants argued strongly that foundations can also experience softening, most thought that the FSS concept should be applied only to the slopes of excavations and embankments.

Almost all participants felt that because an embankment subjects its foundation to increased stresses, the foundation will become stronger over time, not weaker, even if the foundation approaches the normally consolidated state under the increased stress. For these reasons, the FSS concept is not applicable to embankment foundations. Figure 4 shows how overconsolidated foundation clay can become normally consolidated when subjected to increased pressure under an embankment. Because the FSS is for practical purposes the same as the normally consolidated strength, the question of whether the foundation clay is "fully softened" or "normally consolidated" is one of semantics. The strength is the same in either case.

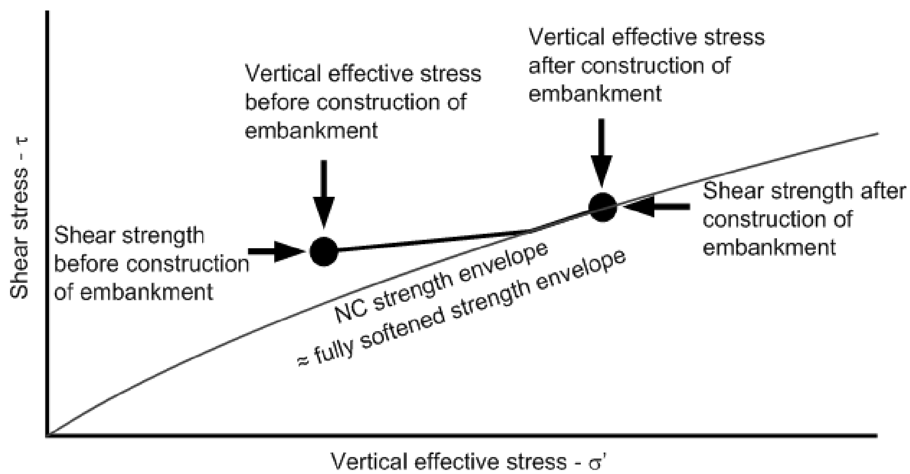

Figure 4 Foundation shear strength before and after embankment construction – one possibility

In the case of embankment foundations, the subtle distinction between "strength" and "strength envelope" is important. As shown in Figure 4, the discrete value of shear strength of the clay in an embankment foundation can increase, while at the same time the clay is moving from a higher overconsolidated strength envelope to the lower normally consolidated or fully softened strength envelope.

Softening caused by recent weathering should be distinguished from soft, weak soil and rock layers that have weathered in geologic time. The latter condition should be evident from adequate site exploration. Engineers planning subsurface explorations for embankment foundations must be familiar with the geologic setting so that high quality samples of potentially weak foundation layers are obtained and tested. Most thought the strength of an embankment foundation can be determined by high quality conventional exploration and testing without invoking the concept of FSS.

RESEARCH NEEDS FOR FULLY SOFTENED STRENGTH

Many research topics were discussed during the workshop. The topics deemed worthy of immediate study are listed below.

Role of progressive failure in the appropriate use of FSS. The use of FSS accounts for softening of the soil due to weathering, an increase in water content due to dilation, and other physical factors. However, in a semi-empirical fashion, it also accounts for progressive failures of slopes (Skempton 1970). The role of progressive failure should be examined using numerical analyses that will accommodate strain softening behavior.

Update of Corps of Engineers EMs to account for FSS. The current engineering manuals used by the Corps of Engineers mention FSS only briefly. The slope stability manual (EM 1110-2-1902) (USACE 2003) mentions that FSS should be used with stiff-fissured clays and shales, but does not mention its use with compacted clays. The levee design manual (EM 1110-2-1913) (USACE 2000) does not mention FSS.

The role of seepage and pore pressures in the use of FSS. The FSS parameters are drained or effective stress parameters, and these are only one component of the determination of the long-term factor of safety. The pore pressures used in effective stress stability analysis are equally important. The opinion was expressed that designers would welcome guidance regarding the applicability of pore pressure coefficients (r_u) in FSS stability analyses.

Correlations of FSS with index parameters. Stark et al.'s (2005) FSS correlation uses Liquid Limit and clay fraction as the entry index parameters. Correlations with other index properties, such as Plasticity Index, percent fines, activity, etc., should be assessed. Future correlations should also examine the prediction of the parameters used to characterize non-linear envelopes, such as power functions. The sample preparation procedures used for the strength tests and index properties should be clearly stated with the correlations.

Laboratory measurement of FSS. Research should be continued to determine the difference in the shear strength parameters obtained from ring shear, direct shear, and triaxial equipment. The influence of sample preparation techniques, pore water chemistry, and soil mineralogy should be examined as part of these investigations. Emphasis should be placed on FSS determined at low effective stresses.

Investigation and cataloging of FSS case histories. Well-documented case histories regarding failures associated with FSS parameters would help to improve understanding of many issues regarding the use and applicability of FSS. In addition to soil properties, the depth of sliding, rainfall history at the site, pore pressures at the time of failure, etc., should be detailed in the documentation. The case histories should include both embankments and excavations.

SUMMARY AND CONCLUSIONS

The August 2011 workshop clarified the current state of knowledge and practice regarding fully softened strength of clays. There was fairly general consensus on several fundamental issues:

- Fully softened shear strengths should be used, with appropriate long-term pore pressures, for analysis of the stability of excavated slopes in highly plastic fissured clays.
- Fully softened shear strengths should be used, with appropriate long-term pore pressures, for analysis of the stability of shallow potential slides in embankments where wet/dry climate cycles are likely to produce significant desiccation cracking. There was disagreement with regard to the use of fully softened strengths for deeper parts of embankments and embankment foundations.
- Laboratory tests should be performed using the same range of effective stresses as will be experienced long-term in the field.
- Curved failure envelopes are more appropriate than linear envelopes for representing fully softened strengths.
- The direct shear test is the most appropriate test for measuring fully softened shear strengths.
- Consideration of local experience with regard to slope performance, recognition of the possible consequences of slope failures, and application of sound engineering judgment are all essential elements of a comprehensive approach to geotechnical engineering of slopes.

Fully softened strength is particularly suited to excavations in stiff fissured clays, such as London clay, and embankments of compacted highly plastic clays subject to desiccation cracking, such as Beaumont clay, Paris clay, and Eagle Ford shale. These conditions share a key characteristic – the possibility for swelling to occur where lateral stresses are reduced by excavation or by development of open cracks. The depths to which softening should be expected in these cases is a subject in need of further investigation.

Lack of consensus on some issues is likely due in part to regional differences in experience with fully softened shear strength that occur as a result of differences in soil and climate. Lessons learned from experience in one region may not be applicable to another region where geology and climate differ. Detailed case studies, and in particular well-documented back analyses of slope failures, will be needed to advance the state of knowledge and practice.

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APPENDIX

Participants in the *Workshop on Shear Strength for Stability of Slopes in Highly Plastic Clays* held at Virginia Tech on August 16 and 17, 2011.

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Klaus, Ken
Koester, Joe
Lucia, Pat
Makdisi, Faiz
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Rodriguez-Marek, Adrian
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Sehn, Al
Shewbridge, Scott
Sills, George
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Smith, Charles
Stark, Timothy
Stephens, Isaac
Suter, Karl
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