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USE AND MEASUREMENT OF FULLY SOFTENED SHEAR STRENGTH

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ABSTRACT

The fully softened shear strength was defined by Skempton (1970) as the peak drained shear strength of a clay in a normally consolidated state. All the experience available on the applicability of the fully softened shear strength for slopes is based on back-analyses. Back-analyses of first-time failures in cuts in stiff-fissured clays and embankments constructed of fat clays have shown that, over a long period of time, the shear strength gets reduced from what is measured in the laboratory using undisturbed samples to the fully softened shear strength. These back-analyses require knowledge or assumption of pore pressures in the slope, which will have a significant influence on the shear strength obtained.

Karl Terzaghi, in 1936, was the first person that qualitatively explained the behavior of cut slopes in stiff-fissured clays. According to Terzaghi (1936), a softening process is initiated by the water percolating into the fissures causing swelling and decreasing the overall shear strength of the clay mass. Investigations presented later by Skempton and his colleagues showed that the controlling shear strength for cuts in stiff-fissured clays was equal to the fully softened shear strength and recommended this shear strength to be used for design (Skempton 1970; Chandler and Skempton 1974; Chandler 1974; Skempton 1977). Skempton (1977) concluded that displacements caused by progressive failure decrease the shear strength of stiff clays toward the fully softened shear strength.

At first, it was believed that only stiff-fissured clays were subjected to softening and that intact clays should be designed using the peak shear strength measured using undisturbed samples (Skempton and Brown 1961; Skempton 1964, 1970). Recent publications have showed that the likelihood of a clay experiencing softening is more dependent on the plasticity of the clay rather than the fissures (Bjerrum 1967; Chandler 1984a; Mesri and Abdel-Ghaffar 1993). Fat clays, when compared to lean clays, tend to be more brittle. This means that fat clays have a more pronounced decrease in shear strength after the peak shear strength is achieved and for this reason are more susceptible to progressive failure.

First-time failures in stiff clays usually occur a long period of time after construction. For this reason, steady state seepage was used in the back-analyses of the case histories presented by Skempton and his colleagues. They found that a pore pressure ratio of 0.3 was applicable to first-

time failures in cuts in stiff-fissured clays (James 1970; Vaughan and Walbancke 1973; Chandler 1974; Skempton 1977).

Investigations presented by Professor Steve Wright and his colleagues of the University of Texas at Austin showed, based on back-analyses, that the fully softened shear strength is also the controlling shear strength of compacted embankments constructed of highly plastic clays (Green and Wright 1986; Kayyal and Wright 1991; Wright 2005; Wright et al. 2007). Steve Wright and his colleagues concluded that weathering, expressed in cycles of wetting and drying, was the main mechanism decreasing the shear strength of compacted clay embankments toward the fully softened shear strength. Failures in this type of projects were found to be shallow (less than 10 ft deep) and to occur numerous years after construction (USACE 1983; Stauffer and Wright 1984; Kayyal and Wright 1991; Wright et al. 2007). A pore pressure ratio ranging from 0.4 to 0.6 was found to be applicable for the case histories analyzed by Wright and his colleagues. Day and Axten (1989) recommended the use of the infinite slope method with seepage parallel to the slope face for slope stability analyses. This same recommendation was presented by Lade (2010). A seepage parallel to the slope face corresponds to a pore pressure ratio ranging from 0.4 to 0.5 for slopes with ratios of 2H:1V to 5H:1V. Failures on compacted clay embankments related to softening have been reported in Texas (Stauffer and Wright 1984; Kayyal and Wright 1991; Wright 2005; Wright et al. 2007), and Mississippi (USACE 1983). According to McCook (2012), softening of this type of structures also occur in Louisiana

To perform slope stability analyses using fully softened shear strength parameter, the type of soils, type of projects, and depths where this shear strength is applicable, and the pore pressures and factor of safety to be used in design should be determined. As stated above, the fully softened shear strength has been found to be the controlling shear strength of cuts in stiff clays and compacted embankments constructed of highly plastic clays. Steady state seepage conditions should be used to design cuts in stiff clays, and a pore pressure ratio ranging from 0.4 to 0.6 or a phreatic surface at the surface of the slope should be used to design compacted embankments made of fat clays.

In cuts in stiff clays, both shallow and deep failures related to fully softened shear strength have been observed. For this type of project, the recommended methodology for design is to assign a curved fully softened failure envelope to the whole slope, search for the critical failure surface, and obtain the factor of safety. This approach will provide the correct factor of safety but the critical surface obtained might not be what is expected to occur *in situ*. Pore pressures corresponding to steady state seepage should be used for design. It should be emphasized that the recommendation to use fully softened shear strength in first-time failures in stiff clays is based on the back-analyses of case histories. Research is required to better understand progressive failure and its influence on the shear strength mobilized *in situ.*

In compacted embankments constructed of fat clays, only shallow failures related to fully softened shear strength have been observed. For this type of projects, the recommended methodology for design is to assign a curved fully softened failure envelope to the whole embankment, search for the critical failure surface, and obtain the factor of safety. If for any reason deep failures are to be considered in designing compacted embankments constructed of fat clays, based on the fact that failures in this type of projects are usually shallow, the first 10 ft below the surface of the slope should be assumed to have a shear strength equal to the fully softened shear strength. Pore pressures should be calculated based on a water table coincident with the slope face.

The fully softened shear strength should not be used in the foundation soil. If any softening occurred in the foundation soil, this should be reflected in the shear strength measured using undisturbed samples. Softening of the foundation soil is not expected to occur after the embankment is constructed.

The consequences of shallow and a deep failures are usually not the same. For this reason, is reasonable that the same factor of safety should not be required for both cases. A shallow failure may be considered by some agencies solely as a maintenance issue. The factor of safety should be based on the uncertainties in the parameters being used for design and the consequences of failure of the structure (Duncan and Wright 2005). The parameters that have more impact on the factor of safety obtained for slope stability are shear strength and pore pressures. The fully softened shear strength is the lowest shear strength expected to be mobilized in first-time slides. This shear strength, coupled with a conservative assumption of pore pressure gives a low uncertainty in the parameters that have the most influence in the factor of safety.

For shallow failures, the consequences of failure are very low. For this reason, if the fully softened shear strength is used, coupled with a water table corresponding to the worst case scenario possible, a factor of safety as low as 1.25 can be used. For deep failures, the consequences of failure will vary depending on the structure. The pore pressure for this type of analyses should be based on the worst seepage condition expected throughout the life of the project. In this case, for structures with low to mid consequences of failure, a factor of safety of 1.35 can be used. For structures with a high consequence of failure, a factor of safety of 1.50 can be used. These factors of safety are based on the recommendations presented by Duncan and Wright (2005) for factors of safety based on uncertainties in the parameters and consequences of failures.

The fully softened shear strength should be measured using normally consolidated remolded specimens as recommended by Skempton (1977). Soil samples should be hydrated for two days using distilled or site-specific water. The soil sample should then be washed or pushed through a No. 40 (425 µm) sieve. To achieve the desired water content, the soil sample cab be air-dried or more water should be added. Water contents equal to or higher than the liquid limit should be used to prepare test specimens for fully softened shear strength measurements.

The direct shear device is recommended for fully softened shear strength measurements. The Bromhead ring shear device does not provide accurate values of fully softened shear strength. The triaxial device requires more time and effort to measure the fully softened shear strength and provides about the same fully softened shear strength as the direct shear device.

The fully softened shear strength failure envelope can be estimated using the correlation presented in Figure 6.59 for the parameters required for Equation 4.1. This correlation is only intended to be used in preliminary design or if better information is not available. Laboratory determination of fully softened shear strength is always recommended for final designs. If this is not possible, the confidence limits presented in Figure 6.59 should be used to determine the fully softened shear strength parameters.