Drained Residual Strength of Cohesive Soils[a]

Discussion by Robert W. Day,[3] Fellow, ASCE

The authors have prepared an important paper on the drained residual shear strength of cohesive soil. The authors have developed a chart (Fig. 4) that can be used to determine the drained residual friction angle for different values of liquid limit, clay fraction, and effective normal stress.

Skempton (1964) stated that the residual friction angle is independent of the original shear strength, water content, and liquidity index, and depends only on the size, shape, and mineralogical composition of the constituent particles. The authors' correlation (Fig. 4) attempts to account for the size, shape, and mineralogical composition of the constituent particles through the use of the liquid limit and clay content. The authors present two case histories, the Gardiner Dam and the Portuguese Bend Landslide, where the back-calculated residual friction angles from stability analyses were almost identical to the values from the authors' correlation (Fig. 4). Three additional case histories are as follows.

Slide at Jackfield, England

Fig. 9 is reproduced from Bjerrum (1967) and shows the slide at Jackfield. The residual friction angle from laboratory testing is 19° and the back-calculated value from stability analyses is 17° (table 1, Bjerrum 1967). Using the authors correlation (Fig. 4), the residual friction angle is 23°.

Slide at Walton's Wood

The slide at Walton's Wood is described by Skempton and Hutchinson (1969). Laboratory shear tests on samples of the slip surface gave consistent results of residual friction angle = 13°. Using the authors correlation (Fig. 4), the residual friction angle is 17°.

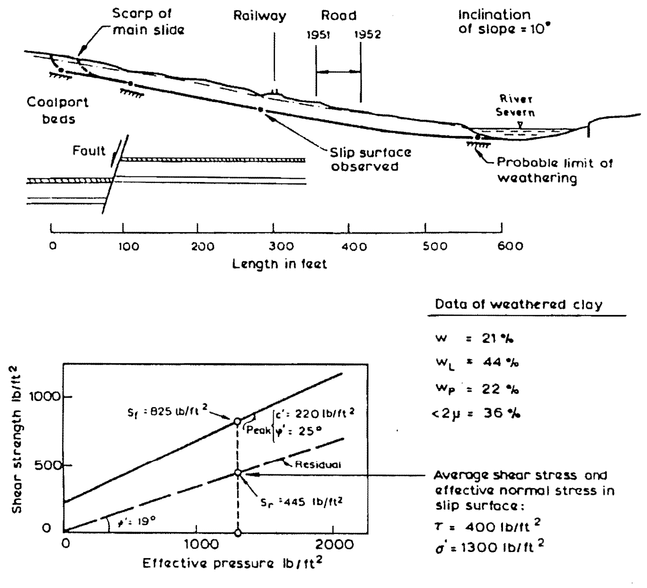

FIG. 9. Slide at Jackfield, England [Reproduced from Bjerrum (1967), Originally from Skempton (1964)]

Slide at River Beas Valley

The slide at River Beas Valley is described by Skempton and Hutchinson (1969). Reversal shear tests on a sample of the clay gave a residual friction angle = 15°. Using the authors' correlation (Fig. 4), the residual friction angle is 24°.

These three case histories show that the authors' correlation (Fig. 4) overestimated the residual friction angle by 20–60%. The size, shape, and mineralogical composition of the constituent particles determine the residual friction angle, which may not be precisely modeled by the liquid limit and clay fraction.

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Discussion by Milan Maksimović[4]

The authors have produced correlation charts in Fig. 3 and Fig. 4 for an estimate of the failure envelope relating the angle ϕ'_r to particular stress levels of 50 kPa, 100 kPa, 400 kPa, and 700 kPa. It is discusser's opinion that such a presentation is rather arbitrary and not very suitable for computer implementation. It would be better if the correlation had been presented in such a manner that could permit the description of the nonlinear failure envelope in some general analytical form and to state the possible scatter. To show that this is possible, the discusser has processed the results of the shearing strength on Altamira bentonitic tuff (ABT) shown in Fig. 1 using the general expression proposed in Maksimović (1988, 1989a,b, 1992) in the form

$$\phi'_r = \phi'_{B,r} + \frac{\Delta\phi'_r}{1 + \dfrac{\sigma'_n}{p_{N,r}}} \tag{1}$$

where $\phi_{B,r}$ = basic angle of residual friction; $\Delta\phi'_r$ = maximum angle difference for the residual strength; and $p_{N,r}$ = median angle pressure for the residual strength.

The residual strength envelope and the variation of ϕ'_r with the stress level in linear and the semilog plot are shown as Fig. 10 and Fig. 11. The curve fits the data with remarkable accuracy. Unfortunately, other 32 listed test samples could not be processed in the same manner, because the complete numerical database in the paper is missing. It is the discusser's experience (Maksimović 1993) that any correlation on the nonlinear shearing strength of soil should be presented in terms of parameters ϕ'_B, $\Delta\phi'$, and p_N. The only correlation that explicitly describes the nonlinearity of the residual failure envelope in a normalized form known to the discusser is the one by Skempton (1985). The result of regression analysis of the mentioned numerical correlation performed by discusser is that for the range of values $(\phi'_r)_{100} = 6° \div 16°$ the value of the mean angle pressure is practically constant $p_N \approx 120$ kPa. The discusser will adopt this value, and focus only on the soil type of high plasticity [liquid limit (LL) > 50%]. After some iteration on the author's correlation, reviewing of results summarized by Lupini et al. (1981) and personal data-

[a]May, 1994, Vol. 120, No. 5, by Timothy D. Stark and Hisham T. Eid (Paper 909).

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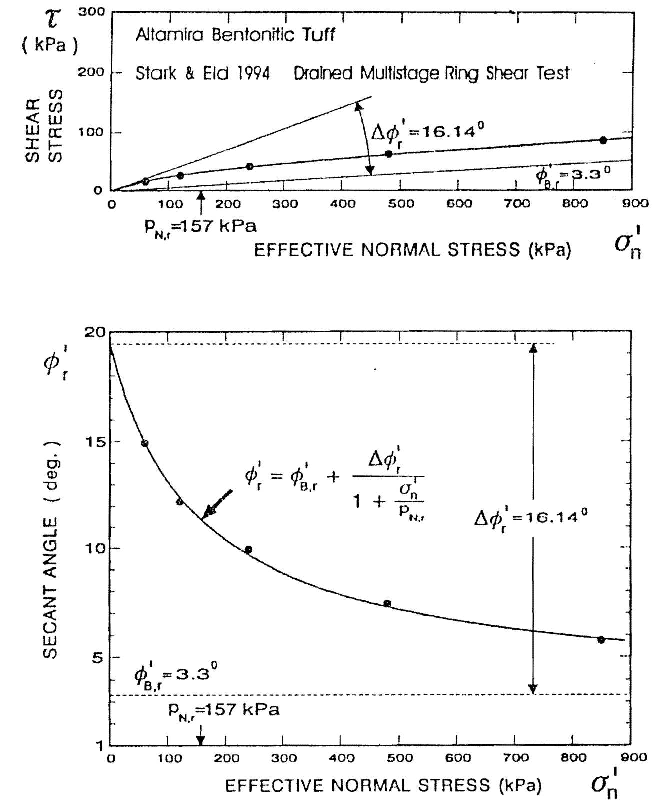

FIG. 10. Interpretation of Test Results: (a) Nonlinear Failure Envelope; (b) Relationship between Secant Angle of Residual Shearing Resistance and Effective Normal Stress in Linear Scale

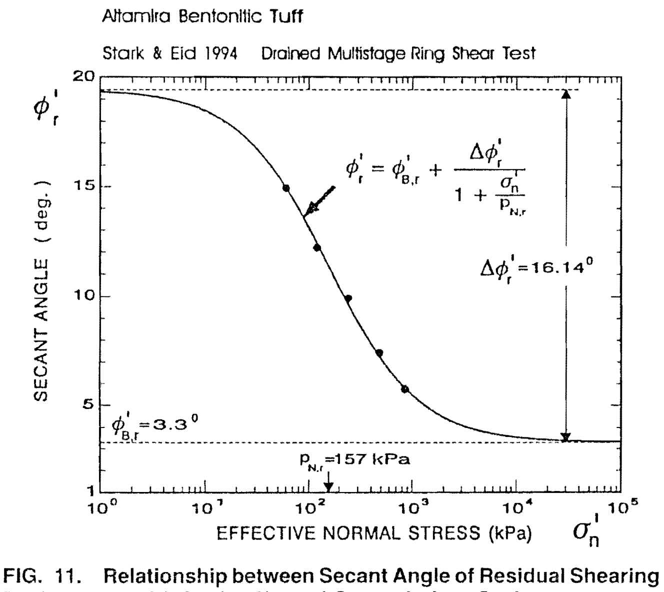

FIG. 11. Relationship between Secant Angle of Residual Shearing Resistance and Effective Normal Stress in Log Scale

base, an alternative correlation is derived for clays with CF $> 42\%$ using parameters, $\Delta\phi'$, ϕ'_B, and p_N as shown in Fig. 12. The main advantage of such an approach is that the angle of residual shearing resistance is described as a continuous function of both the liquid limit and the stress level. In order to check both correlations, the variation of the secant angle with the normal effective stress for a set of values of liquid limit ranging from 50% to 200% is drawn in Fig. 13. The correlations between residual strength and soil index properties cannot be general due to the following findings:

1. The alternative correlation fits authors' proposal for normal stresses of 50 kPa, 100 kPa, and 700 kPa within the

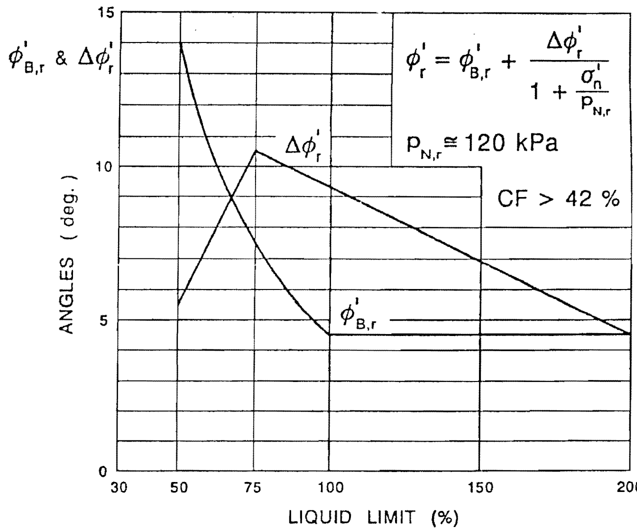

FIG. 12. Alternative Correlation: Relationship between Parameters for Nonlinear Envelope of Residual Shearing Resistance and Liquid Limit

negligible difference, but the line in Fig. 4 presumably corresponding to 400 kPa is about 1° to high. The authors have applied linear interpolation between the values for 100 kPa and 700 kPa. The linear interpolation in semilogarithmic plot is much more appropriate (Fig. 11).

2. Comparison of results of testing on ABT (LL = 96% ÷ 98% ≈ 100%) with correlation over the whole range of practical importance shows that for the normal stress of 100 kPa the correlation underestimates actually measured ϕ'_r by about 40%, but the correlation for LL = 75% would correctly predict the stability of the shallow landslide. However, the correct angle $(\phi'_r)_{500} = 6.6°$ is obtained.

3. An alternative correlation predicts $(\phi'_r)_{95} = 8.9°$ for Bearpaw shale, the difference of 10% being acceptable for this kind of correlation.

Factor of safety (FS) (Table 2) for the actually measured nonlinear failure envelope FS = 1.02 is excellent. However, the analysis based on average reported angles that shows the difference of 4% is not correct. The difference must be about 6%.

Conclusion that the authors draw from results of analyses of two landslides shown in Table 3 can be quite misleading, and the claim that the proposed correlation is much better than the quoted ones can be hardly justified. The problem can be posed the other way around. Would the proposed correlation be acceptable when applied to the case histories from which other correlations have been derived? The check at hand revealed that the discusser's correlation (Maksimović 1989) based on plasticity index not considered by the authors, would predicted the value $(\phi'_r)_{500} = 6.1° \div 6.5°$ and that would be probably the closest value to the actual one of 6.5°. The prediction by Skempton (1985) would be much better than the one that authors attribute to his correlation, if it had been extended to the proper stress level.

The authors recommend that the nonlinear failure envelope or a residual friction angle corresponding to the average normal stress on the slip surface be used in a stability analysis. The discusser agrees with the former, but not with the later recommendation. Both approaches would yield similar results only in the case of long slab-like landslides, with minor variations of normal stresses along the slip surface. For deeper and shorter slides with any slip surface of general form, with significant variation of normal stresses, only the use of the nonlinear envelope would be advisable, as the application of the average angle will be an additional source of error that

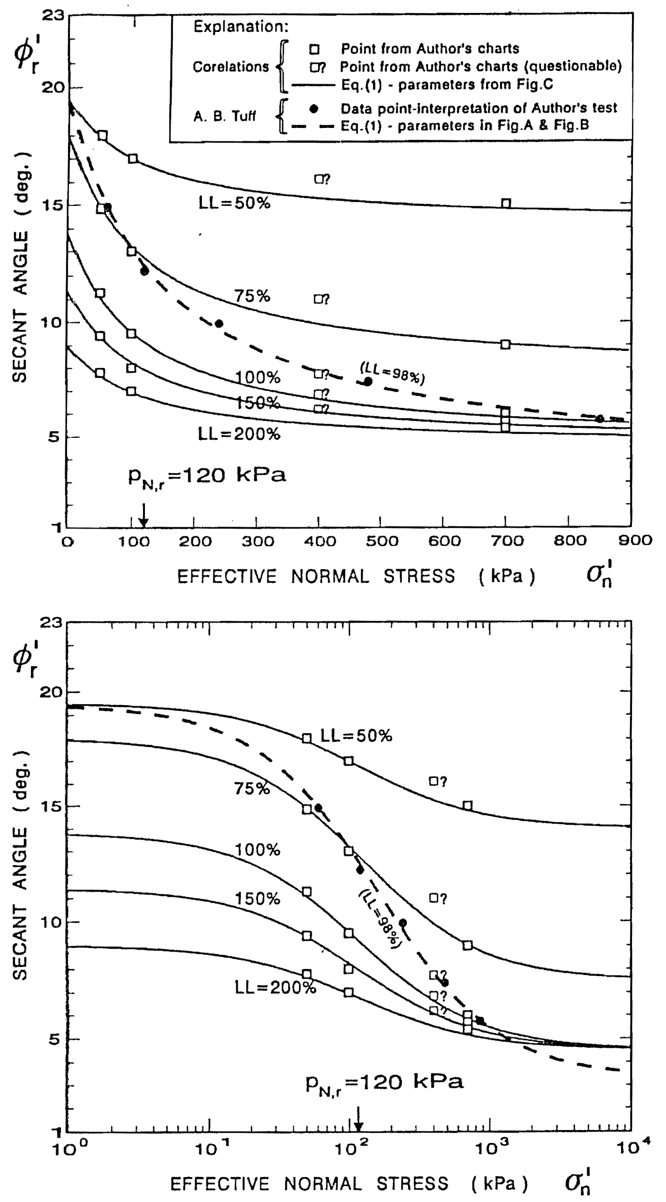

FIG. 13. Relationship between Secant Angle of Residual Shearing Resistance, Liquid Limit, and Stress Level: (a) Normal Effective Stress in Linear Scale; (b) Normal Effective Stress in Log Scale

might exceed 5% on the unsafe side. To minimize the influence of alternative assumptions, the nonlinear failure envelope should be used in general. Even in the most ideal conditions, stability analysis and laboratory tests cannot yield results with an accuracy better than about ±10% (Skempton 1985), and it is unlikely that any general correlation based only on index properties can yield higher accuracy. The possible error of ±30% can be expected, in spite of the fact that it amounts to ±2–3° only. In terms of the proposed correlation shown in Fig. 12, for an estimate of the possible scatter, the value of $\Delta\phi'_r$ can be altered by ±30% and the value of $p_{N,r}$ can be multiplied by a factor in the range from 0.2 to 1.3.

The modelling of the nonlinear failure envelope with 19 data points in computer program is not quite convenient, particularly when the sensitivity study is performed on the actual slope. Analytical description of the failure envelope in the form of (1) is suitable for implementation as a standard feature of a slope stability software and applicable in general, because it is valid not only for the residual shearing strength, but after omitting the subscript r in all parameters, it is applicable to the peak strength of clay, silt, sand, gravel, rockfill, and rock discontinuities.

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Closure by Timothy D. Stark,[5] Associate Member, ASCE, and Hisham T. Eid,[6] Student Member, ASCE

The writers appreciate the comments of both Day and Maksimović.

Day utilizes three case histories to suggest that the proposed relationship (Fig. 4) overestimates the drained residual friction angle. These three case histories (Table 4) involve failure through a mudstone or shale (Henkel and Skempton 1954; Skempton 1964; Skempton and Hutchinson 1969; Early and Skempton 1972). Most heavily overconsolidated clays, mudstones, or shales possess diagenetic bonding that results in aggregates of individual clay particles. The degree of mudstone or shale aggregation that survives a particular sample preparation procedure has an important influence on the measured index properties, such as liquid limit and clay-size fraction (La Gatta 1970; Townsend and Banks 1974). Since the liquid limit and clay-size fraction are used to infer clay mineralogy and the quantity of particles smaller than 0.002 mm, respectively, the clay particles were disaggregated during this study by ball-milling a representative air-dried sample until all particles passed U.S. standard sieve No. 200 (Mesri and Cepeda-Diaz 1986).

The effect of sample preparation on measured index properties of shale can be illustrated by comparing the liquid limit measured using the ASTM Standard Procedure D4318 ("Standard" 1994) and ball-milling. For example, the liquid limit of Lower Pepper shale from the Waco Dam site was measured to be 70% and 94% for the ASTM and ball-milling procedures, respectively. La Gatta (1970) increased the liquid limit of a Cucaracha shale sample from 49% to 156% by crushing it for 6 min in a disc mill. The higher the aggregation of mudstone or shale fabric, the higher the difference in the liquid limits measured using the ASTM and ball-milling procedures.

The Jackfield and Walton's Wood case histories that Day presents involve the Upper Carboniferous Stratum in northern England. Skempton (1964) describes the weathered clay in which these two slides occurred as quite firm and still retaining the characteristics of an overconsolidated clay but "far less strong than the hard, almost rocklike, unweathered strata." Henkel and Skempton (1954) describe this clay as "very heavily overconsolidated." Therefore, it is anticipated that the weathered clay is aggregated. The third case history

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TABLE 4. Description of Field Case Histories

Site (1)	Stratum (2)	Liquid limit (%) (3)	Plastic limit (%) (4)	Clay size (%) (5)	Average effective normal stress on slip surface (kPa) (6)	Residual friction angle (Back-analysis) (degrees) (7)	Residual friction angle (Stark & Eid, 1994) (degrees) (8)	References (9)
Jackfield	Carboniferous rock	45	20	42	65	17	23	Henkel and Skempton (1954)
Walton's Wood	Carboniferous rock	57	27	70	55	13.5–15.5	17	Skempton (1964) Early and Skempton (1972)
River Beas Valley	Siwalik rock	41	25	32	200	18–20	23	Henkel and Yudhbir (1966) Skempton and Hutchinson (1969)

involves shear zones in the clay-shales of the Siwalik rocks. Henkel and Yudhbir (1966) in describing the slickensided surfaces in the Siwalik rocks state that "similar shear zones have been observed in the clayey strata in the folded carboniferous rocks of northern England." Therefore, this clay is most probably also aggregated.

In summary, ball-milling these soils would probably result in higher values of liquid limit and clay-size fraction than the reported values. This increase in liquid limit and clay-size fraction will reduce the value of secant residual friction angle estimated from the proposed relationship in Fig. 4. This reduction will probably yield agreement with the back-calculated values of residual friction angle. For example, the range in secant residual friction angle for Lower Pepper shale from Fig. 4 is 10° to 7° at an effective normal stress of 400 kPa for liquid limits of 70% and 94%, respectively.

In the Jackfield case history, the clay-size fraction is reported as 42% (Table 4). This is near the boundary between the intermediate (25–45%) and high (>50%) clay-size fraction groups in the proposed relationship (Fig. 4). It is anticipated that ball-milling would increase the liquid limit and raise the clay-size fraction to greater than 50%. If so, the estimated residual friction angle would probably be in good agreement with the back-calculated residual friction angle.

In summary, drained residual friction angle is controlled by the size and shape of the soil particles. The shearing process that takes a clay or shale to the residual condition appears to disaggregate soil particles, and thus residual friction angle reflects the shearing resistance of disaggregated soil particles (Chandler 1969; Mesri and Cepeda-Diaz 1986). If index properties are used to characterize residual strength, then the clay or shale sample used for index tests must be disaggregated. Otherwise, inconsistent values of index properties will be measured with an arbitrary degree of disaggregation. Ball-milling is a practical technique for disaggregating particles, and thus it was selected for use during the present study.

The writers agree with Maksimović that using the entire nonlinear residual failure envelope in stability analyses may be applicable to more situations than using a secant residual friction angle corresponding to the average effective normal stress on the slide surface. The writers recommend using engineering judgment to determine whether the nonlinear residual failure envelope or a representative residual friction angle should be used in stability analyses.

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POTENTIAL FOR SEEPAGE EROSION OF LANDSLIDE DAM[a]

Discussion by Robert W. Day,[4] Fellow, ASCE

The authors should be congratulated on a fascinating study on Castle Lake, Wash., which was created by the blockage of Castle Creek during the eruption of Mount St. Helens in 1980. The authors refer to the blockage of Castle Creek as a debris avalanche. But because the material that blocked Castle Creek is a loose soil (no cobbles or boulders, per the authors' Table 2), which traveled about 6 km (4 mi) prior to deposition, perhaps a better description would be an earthflow (Varnes 1978).

The authors state that they performed drained shear strength tests on the earthflow that blocked Castle Creek and obtained effective cohesion values ranging from 5.8–48 kPa (120 to 1,000 psf). These values of effective cohesion are unreasonable given the nature of the earthflow, which is a silty sand

[a]July, 1994, Vol. 120, No. 7, by William Meyer, R. L. Schuster, and M. A. Sabol (Paper 1453).

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