Reprinted from Stability and Performance of Slopes and Embankments II Proceedings
GT Div/ASCE
Berkeley, CA, June 29-July 1, 1992

COMPARISON OF FIELD AND LABORATORY RESIDUAL STRENGTHS

Timothy D. Stark[1], A.M.ASCE and Hisham T. Eid[2], S.M.ASCE

ABSTRACT: A field case history is used to illustrate the accuracy of drained residual strengths measured using torsional ring shear and reversal direct shear apparatuses. The ring shear tests conducted on remolded specimens yielded drained residual strengths that are in excellent agreement with the field case history. The reversal direct shear tests on remolded and precut, remolded specimens yielded factors of safety that are 60 to 10 percent higher, respectively, than the correct value of 1.00. Therefore, it is recommended that a ring shear apparatus and remolded specimens be used to estimate the field residual strength.

The major advantages of the torsional ring shear test are that the soil is sheared continuously in one direction for any magnitude of displacement, the cross-sectional area of the shear plane is constant during shear, a thinner specimen allows a faster displacement rate to be used, and less laboratory supervision is required.

INTRODUCTION

Skempton (1964, 1970, and 1985) has drawn considerable attention to the nature and engineering significance of the drained residual strength. The drained residual strength is applicable to cases where a pre-existing shear surface is present, such as in old landslides, sheared bedding planes, and sheared joints

1 Asst. Prof. of Civ. Engrg., Univ. of Illinois at Urbana-Champaign, 2217 Newmark Civ. Eng. Lab, Urbana, IL 61801.

2 Research Asst., Dept. of Civ. Engrg., Univ. of Illinois at Urbana-Champaign, Urbana, IL.

or faults. Skempton (1970 and 1985) concluded that the drained post-peak drop in strength observed in overconsolidated clays is due to 1.) an increase in water content due to dilation and 2.) the orientation of clay particles parallel to the direction of shearing. In normally consolidated clays the drained post-peak drop is due entirely to the orientation of clay particles parallel to the direction of shearing. Large shear displacements in one direction are required to reorient the clay particles and obtain a drained residual strength condition.

At the present time, the reversal direct shear test is widely used to measure the drained residual strength of clays even though it has several limitations. The primary limitation is that the soil is sheared forward and then backward until a minimum or equilibrium shear resistance is measured. Each reversal of the shear box results in a horizontal displacement that is usually less than 1.3 cm (0.5 inches). As a result, the specimen is not subjected to continuous shear deformation in one direction and thus only a partial reorientation of the clay particles is obtained. In addition, the cross-sectional area of the specimen is changing during shear and a substantial amount of soil is usually extruded out of the exposed shear plane during the test. These and other limitations usually result in residual strengths that are higher than the residual values obtained from a torsional ring shear device.

The main advantage of the torsional ring shear device is that it shears the soil continuously in one direction for any magnitude of displacement. This allows full orientation of the clay particles parallel to the direction of shear and the development of a true residual strength condition. Other advantages of the ring shear device include a constant cross-sectional area of the shear plane during shear, a thinner specimen, which allows faster consolidation and the use of a faster drained displacement rate, more reproducible results, and less laboratory supervision than the reversal direct shear test.

The Bromhead (1979) ring shear apparatus is becoming more widely used because of its cost, availability, and ease of operation. Bromhead and Curtis (1983) showed that this apparatus yields results that are in good agreement with those obtained using the ring shear apparatus developed by the Norwegian Geotechnical Institute and Imperial College (Bishop et al. 1971). Bromhead and Dixon (1986) showed that the residual strengths measured using the Bromhead apparatus and remolded specimens are in excellent agreement with back-calculated values for the landslide at Warden Point. It should be noted that a remolded specimen consists of remolded soil that is not precut prior to shear. Newbery and Baker (1981) showed that Bromhead ring shear tests on remolded specimens are also in good agreement with slip surface tests on shear zone material from the Wenallt slip. A slip surface test is a direct shear test conducted on an undisturbed specimen with a fully developed slip surface located exactly at the shear plane of the direct shear box. The specimen is arranged such that shearing follows the natural direction of movement. Skempton (1985) showed that slip surface tests provide an accurate estimate of the field residual strength. However, slip surface tests are significantly more difficult to perform than a ring shear test on remolded specimens.

In summary, the drained residual strength measured using the Bromhead ring shear apparatus and remolded specimens appears to be in good agreement with the field residual strength. However, most of the case histories used to investigate the accuracy of this apparatus involve London Clay. This paper presents a case history from Southern California that illustrates the effect of test specimen (remolded versus precut, remolded) and testing apparatus (ring shear versus direct shear) on the measured residual strength.

FIELD CASE HISTORY

The case history involves a site in Southern California that is underlain by the Santiago Formation. At this site the Santiago Formation is composed of a claystone and a sandstone. The sandstone overlies the greenish- to bluish-gray claystone and is fine- to medium-grained. The clay beds and clay seams that exist are usually horizontal and consist of sheared claystone. The claystone is commonly fissured displaying slickensided and shiny parting surfaces (Figure 1). The remolded claystone classifies as a clay or silty clay of high plasticity, CH-MH, according to the Unified Soil Classification System. The liquid limit, plasticity index, and clay fraction (percentage by weight of particles smaller than 0.002 mm) are 89, 45, and 57 percent, respectively.

The landslide occurred along a bluff approximately 18 to 20 meters (60 to 65 feet) high. The length of the scarp is approximately 130 meters (430 feet) and the slide encompassed approximately 120,000 cubic meters (140,000 cubic yards) of soil. At the mid-point of the slide mass, the bluff turns from a northerly direction to an easterly direction at an angle of 90 to 100 degrees. The cross-sections in Figures 2, 3, and 4 illustrate the subsurface conditions through the slide. Figures 2 and 4 are through north and east trending sections of the bluff. Figure 3 depicts the subsurface conditions through the middle of the slide mass where the orientation of the bluff line changes. These three cross-sections were chosen to represent the range of effective normal stresses acting on the slide plane.

Fig. 1. Typical Slickensided Surfaces in Claystone

This case history was selected because the site has undergone at least three episodes of landsliding prior to the slide that was back-analyzed. Skempton (1977) stated that 1 to 2 meters (3 to 6 feet) of field displacement is required to mobilize the residual strength condition. Clearly, this site has undergone displacements greater than 2 meters (6 feet) in recent geologic history, and thus has probably developed a residual strength condition. In addition, the majority of the slide plane is approximately horizontal through the Santiago Formation. This indicates that the slide occurred along a claystone seam or layer, which allows the shear strength of this layer to be approximated by one set of shear strength parameters. The slide plane was located using slope inclinometers and extensive borings and trenches. The ground water levels were extensively monitored using piezometers and the water levels in the borings and trenches. These observations resulted in the phreatic surface that is shown in the cross-sections.

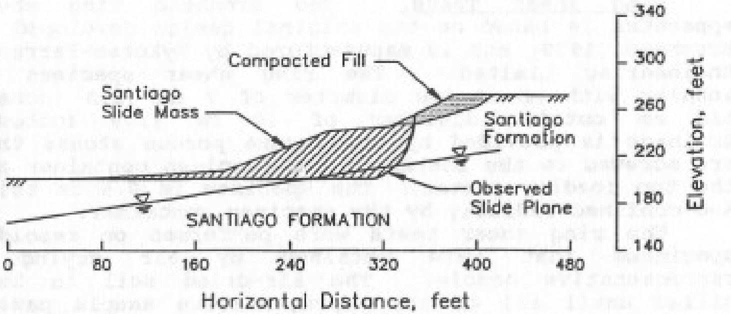

Fig. 2. Cross-Section Through North Trending Bluff

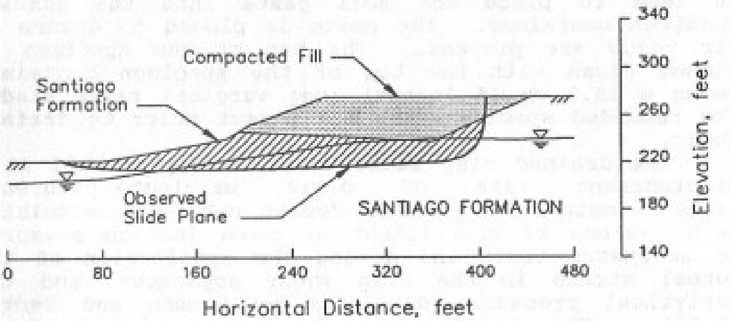

Fig. 3. Cross-Section Through Middle of Slide Mass

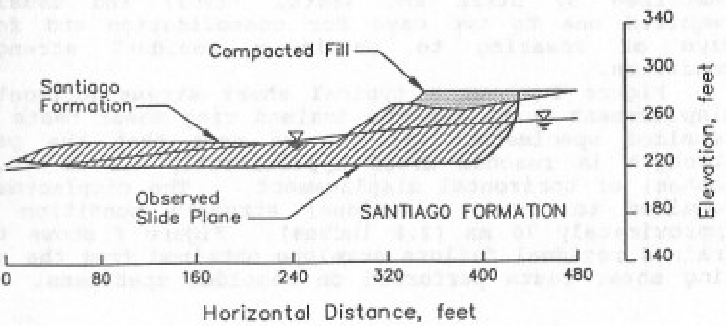

Fig. 4. Cross-Section Through East Trending Bluff

LABORATORY RESIDUAL STRENGTHS

Ring Shear Tests. The Bromhead ring shear apparatus is based on the original design developed by Bromhead (1979) and is manufactured by Wykeham-Farrance Engineering Limited. The ring shear specimen is annular with an inside diameter of 7 cm (2.8 inches) and an outside diameter of 10 cm (3.9 inches). Drainage is provided by two bronze porous stones that are screwed to the bottom of the specimen container and the top loading platen. The specimen is 0.5 cm thick and confined radially by the specimen container.

The ring shear tests were performed on remolded specimens that were obtained by air drying a representative sample. The air-dried soil is ball milled until all of the representative sample passes the No. 200 sieve. Distilled water is added to the pulverized soil until a liquidity index of approximately 1.5 is obtained. The sample is then allowed to rehydrate for at least one week. A spatula is used to place the soil paste into the annular specimen container. The paste is placed to ensure no air voids are present. The top of the specimen is planed flush with the top of the specimen container using a 15.2 cm (6 inches) long surgical razor blade. The remolded specimens are not precut prior to drained shear.

The drained ring shear tests were performed at a displacement rate of 0.018 mm/minute (0.0007 inches/minute). This displacement rate was calculated using values of coefficient of consolidation measured in oedometer tests and during the application of the normal stress in the ring shear apparatus, and the analytical procedure developed by Gibson and Henkel (1954). The coefficient of consolidation used to estimate this displacement rate is 1.35 mm^2/minute (0.002 $inches^2$/minute). The ring shear tests were performed using the Bromhead ring shear test procedure described by Stark and Vettel (1992) and usually required one to two days for consolidation and four days of shearing to obtain a residual strength condition.

Figure 5 shows a typical shear stress-horizontal displacement curve for the drained ring shear tests on remolded specimens. It can be seen that the peak strength is reached after approximately 1.0 mm (0.06 inches) of horizontal displacement. The displacement required to reach a residual strength condition is approximately 70 mm (2.8 inches). Figure 6 shows the drained residual failure envelope obtained from the six ring shear tests performed on remolded specimens. It can be seen that the envelope is slightly nonlinear at effective normal stresses greater than 150 kPa (3130 psf).

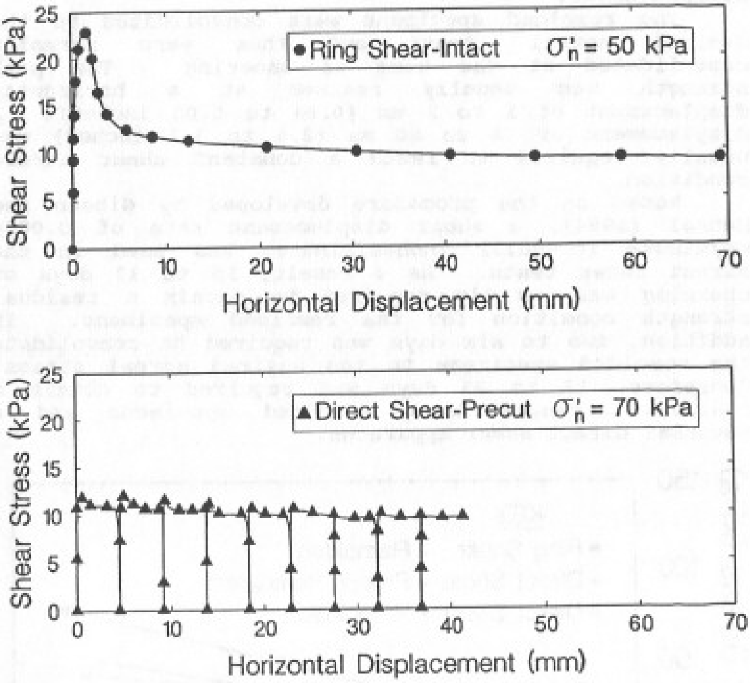

Fig. 5. Typical Shear Stress-Horizontal Displacement Curves from Ring Shear and Direct Shear Tests

<u>Reversal Direct Shear Tests.</u> The reversal direct shear tests were performed using a direct shear apparatus manufactured by Wykeham-Farrance Engineering Limited. The direct shear specimen is square with dimensions of 6-by-6 cm (2.4-by-2.4 inches). The thickness of the speçimen is 3.8 cm (1.5 inches). The shear box was reversed manually at the end of each travel. The horizontal displacement of each travel is approximately 0.5 cm (0.2 inches). The direct shear tests were performed on remolded and precut, remolded specimens. The remolded specimens were obtained using

the ring shear specimen preparation procedure previously described. The precut, remolded specimens consist of a remolded specimen that is precut prior to drained shear.

The remolded specimens were consolidated to the desired normal stress and thus were normally consolidated at the time of shearing. The peak strength was usually reached at a horizontal displacement of 1 to 2 mm (0.04 to 0.08 inches). A displacement of 74 to 80 mm (2.9 to 3.1 inches) was usually required to reach a constant shear stress condition.

Based on the procedure developed by Gibson and Henkel (1954), a shear displacement rate of 0.0034 mm/minute (0.000132 inches/minute) was used in the direct shear tests. As a result, 15 to 17 days of shearing was usually required to obtain a residual strength condition for the remolded specimens. In addition, two to six days was required to consolidate the remolded specimens to the desired normal stress. Therefore, 17 to 23 days was required to obtain a residual strength using remolded specimens and a reversal direct shear apparatus.

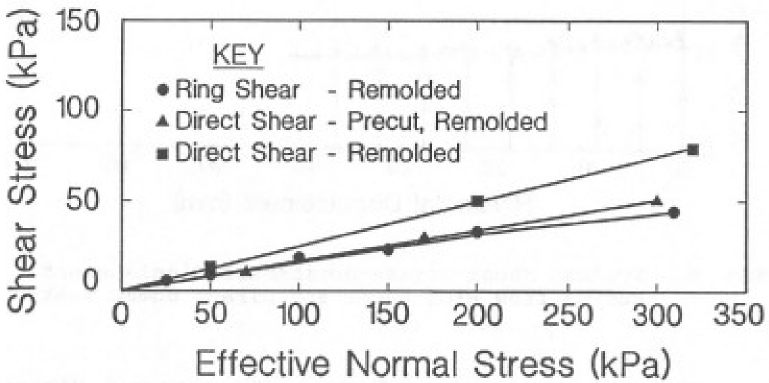

Fig. 6. Drained Residual Failure Envelopes for Claystone

Figure 6 illustrates the failure envelope obtained from the three drained direct shear tests on remolded specimens. It can be seen that the envelope is linear and corresponds to an effective friction angle of approximately 14.5 degrees. This envelope is significantly higher than the ring shear envelope and it will be seen that it significantly overestimates the factor of safety for the field case history. Due to the long test duration (17 to 23 days) and the unconservative residual strengths, reversal direct shear tests on remolded specimens should not be used to estimate the field residual strength.

The precut, remolded specimens were obtained using a special procedure developed by Mesri and Cepeda-Diaz (1986). Each half of the shear box is filled to a thickness of 2 to 2.5 cm (0.8 to 1.0 inches) using the remolded soil paste described previously. The two halves of the shear box are consolidated separately in a oedometer/consolidation frame. Each half is consolidated to 690 kPa (14,400 psf), which usually requires eight to ten days. Each face of the shear surface is consolidated against a Tetko polyester screen (HD 7-6) that is supported by a smooth and flat Teflon plate. After consolidation, the two smooth and flat surfaces are precut using a 15.2 cm (6 inches) long surgical razor blade. This creates a very smooth and polished surface. The two polished surfaces are assembled together and consolidated to the desired normal stress. Therefore, the specimen is overconsolidated prior to shearing and the overconsolidation ratio depends on the desired normal stress. The specimen is sheared in the same direction that the specimens were precut. This results in a specimen that is similar to the one used in a slip surface test.

Figure 5 shows a typical shear stress-horizontal displacement curve for the precut, remolded specimens. This shear stress-horizontal displacement curve is also typical of the direct shear tests on remolded specimens, except that the remolded specimens yielded residual strengths that are approximately 30 percent higher. It is anticipated that the difference is due to the partial reorientation of the clay particles in the remolded specimens. Figure 5 shows that the peak strength is reached after approximately 1 mm (0.04 inches) and the residual strength requires about 40 mm (1.6 inches) of horizontal displacement. Therefore, ten to eleven days of shearing at a displacement rate of 0.0034 mm/minute (0.000132 inches/minute) is required to reach a residual condition with the precut, remolded specimens.

Figure 5 also illustrates the variability of the measured shear stress during each travel of the direct shear box. It can be seen that a peak strength is measured at the beginning of each travel of the shear box and the post-peak strength loss varies with each travel. Clearly, the ring shear apparatus provides a better representation of the gradual decrease in shear stress with increasing horizontal displacement.

It can be seen from Figure 6 that the residual failure envelope obtained from the three drained direct shear tests on precut, remolded specimens is in good agreement with the ring shear envelope except at normal stresses greater than 150 kPa (3130 psf). This envelope is linear and corresponds to an effective friction angle of 9.5 degrees.

Discussion of Ring Shear and Direct Shear Test Results. The precut, remolded specimens required about 30 mm (1.2 inches) less horizontal displacement than the direct shear tests on remolded specimens to obtain a residual condition. The reduced displacement is probably due to the precutting process creating a shear plane and orienting some of the clay particles parallel to the direction of shear. In addition, the stiffness of the overconsolidated specimen probably facilitated the reorientation of clay particles during drained shear.

The ring shear tests on remolded specimens also required approximately 30 mm (1.6 inches) more horizontal displacement to reach a residual condition than the direct shear tests on precut, remolded specimens. This is probably due to the ring shear apparatus having to create a shear plane in the remolded specimen and then orient the clay particles parallel to the direction of shear. Therefore, remolded specimens in a direct shear or ring shear apparatus will require similar horizontal displacements to reach a constant shear stress condition. However, the direct shear apparatus yields significantly higher residual strengths because the specimen is not sheared continuously in one direction.

It is anticipated that use of remolded specimens in the ring shear apparatus yields a good estimate of the field residual strength due to the design of the Bromhead device. In this apparatus the shear plane forms at or near the soil/top porous stone interface. The porous stone is a hard surface that appears to aid the orientation of clay particles parallel to the direction of shear. The use of hard surfaces to facilitate the development of a residual strength condition has been previously reported by Kanji and Wolle (1977). In addition, the soil is sheared continuously in one direction. These factors result in residual strengths that are in good agreement with field case histories even though remolded specimens are used.

COMPARISON OF FIELD AND LABORATORY RESIDUAL STRENGTHS

The factors of safety computed using the three cross-sections in Figures 2, 3, and 4 and the three failure envelopes shown in Figure 6 are presented in Table 1. Spencer's (1967) stability method, as coded in UTEXAS2 (Wright, 1986), was used for the analysis. It should be noted that the nonlinear failure envelope obtained from the ring shear tests was modeled using nineteen data points and the nonlinear failure envelope option in UTEXAS2. The moist unit weight of the compacted fill and Santiago Formation were measured to be 19.6 kN/m^3 (125 pounds/ft^3). The shear strength parameters, c' and ϕ', of the compacted fill were measured using direct shear tests and the values are 12 kPa (250 pounds/ft^2) and 25 degrees, respectively.

It can be seen from Table 1 that the ring shear tests on remolded specimens yielded an average factor of safety of approximately 1.00 for the three cross-sections. In particular, the main cross-section, Figure 3, was in excellent agreement with a factor of safety of 1.00 while the bordering cross-sections, Figures 3 and 5, were in reasonable agreement. Field observations suggest that the slide started near the main cross-section and spread laterally. Therefore, the factor of safety for the main cross-section is probably most representative of the field conditions.

TABLE 1. Calculated Factors of Safety for Ring Shear and Direct Shear Test Results

Test and Specimen Type	Calculated Factor of Safety			Average Factor of Safety
	Northerly Section	Main Section	Easterly Section	
RS-Remold	0.93	0.99	1.08	1.00
DS-Remold	1.49	1.67	1.68	1.61
DS-Precut	0.98	1.10	1.12	1.06

Note: RS-Remold = ring shear tests using remolded specimens; DS-Remold = direct shear tests using remolded specimens; DS-Precut = direct shear tests using precut, remolded specimens

Table 1 also illustrates the factors of safety for the residual strength envelopes obtained from the direct shear tests. It can be seen that the average factor of safety for the remolded specimens is approximately 60 percent higher than the ring shear factor of safety. The direct shear tests on precut, remolded specimens yielded a factor of safety of 1.10 for the main cross-section and an average factor of safety of 1.06. Therefore, direct shear tests on precut, remolded specimens provide an unconservative estimate of the field residual strength. Since the residual failure envelopes for the precut, remolded specimens and the ring shear tests on remolded specimens did not differ significantly, the factor of safety appears to be sensitive to the measured residual strength. Therefore, substantial time and effort should be invested in measuring the drained residual strength.

CONCLUSIONS

A field case history is used to illustrate the accuracy of residual strengths measured using torsional ring shear and reversal direct shear apparatuses. The ring shear tests conducted on remolded specimens yielded residual strengths that are in excellent agreement with the case history. The reversal direct shear tests on precut, remolded specimens yielded a factor of safety that is approximately 10 percent higher than the correct value of 1.00. The direct shear tests on remolded specimens yielded a factor of safety that is 60 percent higher than the correct value.

Based on this field case history, a torsional ring shear apparatus and remolded specimens should be used to estimate the field residual strength. However, reversal direct shear tests using precut, remolded specimens, obtained using the procedure described by Mesri and Cepeda-Diaz (1986), provide a slightly unconservative but reasonable estimate of the field residual strength. It should be noted that the direct shear tests on precut, remolded specimens usually required 18 to 20 days to complete versus 4 to 6 days for remolded specimens in a ring shear apparatus. Therefore, the ring shear apparatus is recommended for engineering practice. Clearly, remolded specimens, i.e., not precut, should not be used in reversal direct shear tests to measure the field residual strength.

ACKNOWLEDGMENT

This study was performed as part of National Science Foundation Grant No. BCS-91-96074. The financial support of the National Science Foundation is gratefully acknowledged. The writers also acknowledge G. Mesri for his many valuable suggestions.

REFERENCES

Bishop, A.W., Green, G.E., Garaga, V.K., Andresen, A., and Brown, J.D., 1971, "A New Ring Shear Apparatus and its Application to the Measurement of Residual Strength," *Geotechnique*, Vol. 21, No. 4, pp. 273-328.

Bromhead, E.N. (1979). "A Simple Ring Shear Apparatus," *Ground Engineering*, Vol. 12, No. 5, pp. 40-44.

Bromhead, E.N. and Curtis, R.D. (1983). "A Comparison of Alternative Methods of Measuring the Residual Strength of London Clay," *Ground Engineering*, Vol. 16, No. 4, pp. 39-41.

Bromhead, E.N. and Dixon, N. (1986). "The Field Residual Strength of London Clay and its Correlation with Laboratory Measurements, especially Ring Shear Tests," *Geotechnique*, Vol. 36, No. 3, pp. 449-452.

Gibson, R.E. and Henkel, D.J. (1954). "Influence of Duration of Tests at Constant Rate of Strain on Measured 'Drained' Strength," *Geotechnique*, Vol. 4, No. 1, pp. 6-15.

Kanji, M.A. and Wolle, C.M. (1977). "Residual Strength-New Testing and Microstructure," *Proc. Ninth Intl. Conf. on Soil Mechanics and Foundation Engineering*, Tokyo, Volume 1, pp. 153-154.

Mesri, G. and Cepeda-Diaz, A.F. (1986). "Residual Shear Strength of Clays and Shales," *Geotechnique*, Vol. 36, No. 2, pp. 269-274.

Newbery, J. and Baker, D.A.B. (1981). "The Stability of Cuts on the M4 North of Cardiff," *Q.J. Engrg. Geol.*, Vol. 14, pp. 195-205.

Skempton, A.W. (1964). "Long-Term Stability of Clay Slopes," *Geotechnique*, Vol. 14, No. 2, pp. 75-101.

Skempton, A.W. (1970). "First-time Slides in Overconsolidated Clays," *Geotechnique*, Vol. 20, No. 4, pp. 320-324.

Skempton, A.W. (1977). "Slope Stability of Cuttings in London Clay," *Proc. Ninth Intl. Conf. on Soil Mechanics and Foundation Engineering*, Tokyo, Special Lecture Volume, pp. 261-270.

Skempton, A.W. (1985). "Residual Strength of Clays in Landslides, Folded Strata and the Laboratory," *Geotechnique*, Vol. 35, No. 1, pp. 3-18.

Spencer, E. (1967). "A Method of Analysis of the Stability of Embankments Assuming Parallel Inter-Slice Forces," *Geotechnique*, Vol. 17, No. 1, pp. 11-26.

Stark, T.D. and Vettel, J.J. (1992). "Bromhead Ring Shear Testing Procedure," ASTM *Geotechnical Testing Journal*, Vol. 15, No. 1, March, pp. 24-32.

Wright, S.G. (1986). "UTEXAS2: A Computer Program for Slope Stability Calculations," Geotechnical Engineering Software GS86-1, Department of Civil Engineering, University of Texas, Austin, pp. 109.