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ANDERSLAND O.B.
Michigan State University, U.S.A.

KHATTAK A.S.
South Dakota State University, U.S.A.

Shear strength of kaolinite/fiber soil mixtures

Cisaillement dans les mélanges kaolinite/fibre

Les paramètres de résistance à la contrainte et de force de cisaillement pour des mélanges de sols faits de fibres de pulpe et de kaolinite ont été étudiés par la méthode du test triaxial.

INTRODUCTION

The stress-strain behavior and shear strength parameters of soils are modified when fiber inclusions are added to an assemblage of particles. Attraction between organic fibers and clay particles provided a bond which permits load transfer through shear when fibers are displaced. This composite action of the clay-water matrix reinforced with a limited amount of fibers resulted in a stiffening action and a higher modulus of elasticity. Ultimate strengths were increased. Optimum combinations needed for desired mechanical properties must be determined on the basis of laboratory tests.

The mechanical behavior of soil mixtures prepared from pulp fibers and kaolinite were observed using the triaxial test. Dry pulp fibers, with a weighted average length of about 1.6 mm, were mixed with dry kaolinite in proportions of 16 and 40 percent fiber by weight. All kaolinite and all fiber samples were included for comparative purposes. Water was added in amounts needed to form a slurry. Consolidation decreased water contents to levels which permitted trimming test cylinders.

Samples with fiber inclusions were tested for undrained and drained conditions. Measurement of pore pressures provided effective stresses for the undrained tests. Increasing fiber contents altered the stress-strain behavior from a brittle to a plastic failure. Consolidated-drained tests and failure based on the peak stress difference and/or 20% axial strain gave shear strength parameters (ϕ') which increased from 20 degrees for kaolinite to 31 degrees for all fiber samples. Consolidated-undrained tests and the same failure criteria gave ϕ' values ranging from 20 degrees for kaolinite to more than 80 degrees for all fiber samples. A new failure criterion, based on the peak value of the stress path defined by the maximum ratio of shear stress to effective normal stress (maximum obliquity), gave intermediate values of ϕ'. Details on sample preparation, laboratory triaxial tests, experimental results and discussion are presented.

EXPERIMENTAL WORK

Materials Studied.--The kaolinite particles included 100% passing 0.04 mm, 93% passing 0.01 mm, and 42% passing 0.001 mm. The grain-size distribution was relatively uniform. Consistency limits included a liquid limit of 47.8%, plastic limit of 27.5%, and plasticity index of 20.3%. The specific gravity of kaolinite particles equal to 2.70 was used in the study.

Pulp fibers, almost pure cellulose, included a range of sizes. A weighted average fiber length of 1.6 mm was determined using the TAPPI (1964) test procedure. Fibers observed in an electron microscope included typical diameters of 0.02 mm. Surface area measurements, using the water vapor absorption method (Perkin-Elmer Corporation, 1961), gave values close to 133 m^2/g of fiber. A value of 1.54 was used for the specific gravity of the pulp fibers.

Sample Preparation.--Pulp fiber board was first freeze dried and separated into a fluffy mass. Selected proportions of dry kaolinite were mixed with the dry fiber. Water was added in amounts needed to form a slurry. This slurry was normally consolidated until the mass formed a soft cylinder from which smaller test samples could be trimmed. A high-speed rotary cutting tool minimized problems with trimming the fibrous soil mixtures. For convenience, all fiber samples were formed by placement of the slurry into a split cylinder mold with the desired dimensions. Kaolinite samples were formed by consolidation of a slurry followed by trimming to the desired size.

Triaxial Tests.--Test samples were mounted in a conventional triaxial cell (Bishop and Henkel, 1962). Isotropic consolidation at selected pressures was continued for a 24 hour period on all samples. A backpressure was used to dissolve air bubbles entrapped in the test samples and to ensure a high degree of saturation. At this stage observed excess pore pressures were recorded for small increases in cell pressure permitting computation of the B pore pressure coefficient. Sample pore pressures were permitted to return to equilibrium values before application of the deviator stress. Typical results, including stress difference, excess pore water pressures, and the A parameter for a consolidated-undrained test on a 40% fiber/60% kaolinite (dry weight basis) sample are shown in Figure 1. A plastic type behavior is observed with failure assumed at 20% axial strain. The A pore pressure parameter at failure equals 0.63. For higher fiber content samples the excess pore water pressures approached confining pressures at axial strains of about 15+%.

The consolidated-drained test followed the same procedures up to the end of consolidation. During application of the deviator stress the sample was permitted to drain with volume change recorded at respective axial strain levels. Time to failure, based on 20% axial strain, was estimated using the coefficient of consolidation, c_v, from the consolidation portion of the test and equations given by Bishop and Henkel (1962). Typical results, including the stress difference and volumetric strain, for a consolidated-drained test on a 40% fiber/60% kaolinite (dry weight basis) sample are shown in Figure 2. A plastic type behavior is observed with failure assumed at 20% axial strain. The change in volumetric strain shows close to a linear relationship with axial strain.

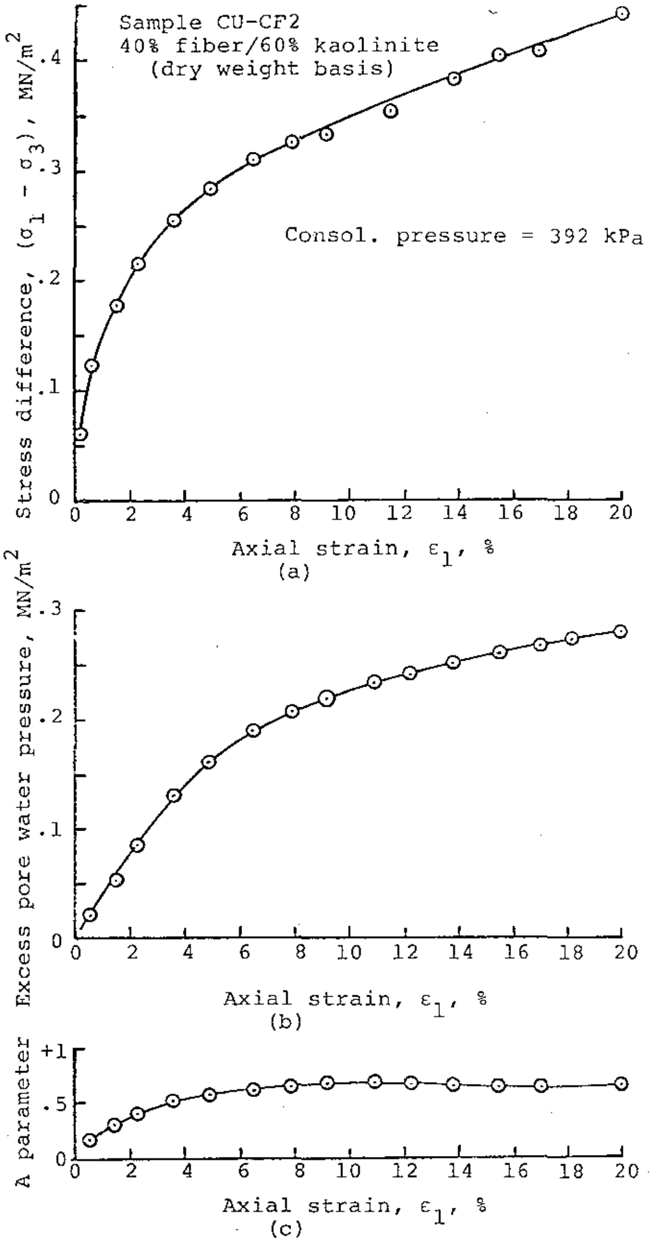

Figure 1. Consolidated-undrained triaxial test on a 40% fiber/60% kaolinite (dry weight basis) sample. (a) Stress difference. (b) Excess pore water pressure. (c) A parameter.

RESULTS AND DISCUSSION

Stress-Strain Behavior.--The addition of fibers to the saturated kaolinite has the initial effect of stiffening the soil mass and increasing the ultimate strength for undrained conditions. This behavior is illustrated in Figure 3 where comparisons are shown for two fiber/kaolinite mixtures, all fiber, and kaolinite test samples. Note that the addition of 16% fiber (dry weight basis) increased the peak stress difference from 189 kN/m^2 to 271 kN/m^2, an increase of 43%. This large increase occurred even though the kaolinite had been consolidated under a greater load, 343 kPa as compared to 294 kPa for the fiber/kaolinite mixture. The stiffness decreased with larger fiber contents. The addition of fibers to the kaolinite alters the stage in the shear pro-

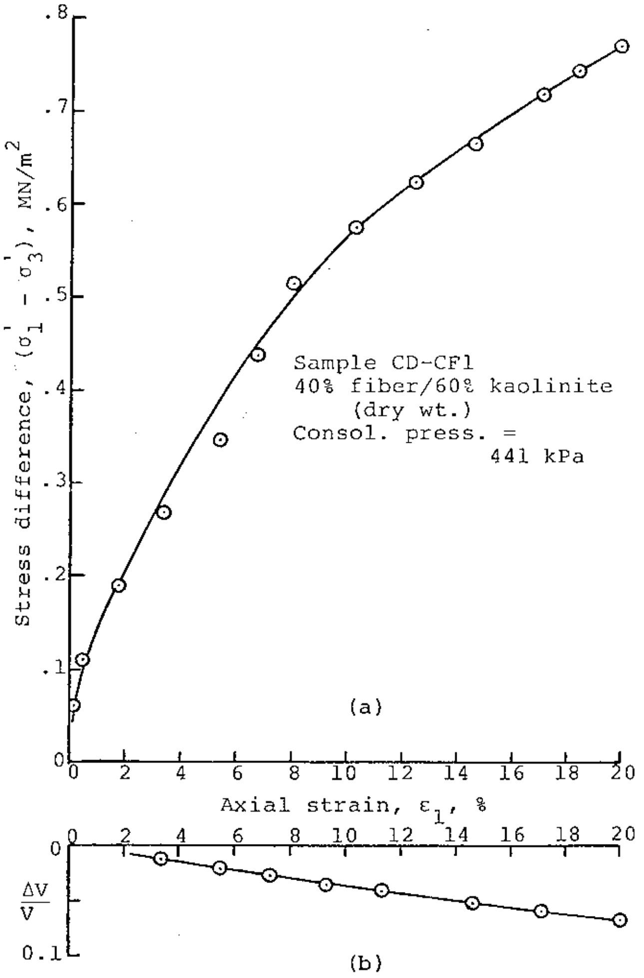

Figure 2. Consolidated-drained triaxial test on a 40% fiber/60% kaolinite (dry weight basis) sample. (a) Stress difference. (b) Volumetric strain.

cess which represents failure. The kaolinite sample developed a peak stress at about 8% axial strain with failure corresponding to a brittle type behavior. All fiber samples continued to increase in strength up to and beyond 20% axial strain with failure by bulging. Intermediate fiber/kaolinite combinations showed a behavior between these extremes. The stress-strain curve did not appear to be affected when excess pore water pressures approached cell pressures for the higher fiber content samples.

Shear Strength Parameters.--Triaxial data for all fiber samples, summarized in Figure 4, give the shear strength parameter ϕ' equal to 80.4 degrees for consolidated-undrained conditions and 31 degrees for consolidated-drained conditions. Data points correspond to assumed failure conditions, either the peak stress or the stress at 20% axial strain. The angle α' in Figure 4 is converted to ϕ' by the relationship $\phi' = \sin^{-1}(\tan \alpha')$. Compare these ϕ' values with 20 degrees observed for both undrained and drained conditions on the kaolinite. Fiber/kaolinite mixtures gave intermediate values for ϕ' as shown in Figure 5 where fiber content has been plotted against the shear strength parameter ϕ'. Individual pulp fibers contain internal pores which allow entry of water molecules and swelling at low pressures. These pores contribute to a high water holding capacity. This fiber structure combined with high water contents and the undrained test condition appear related to high values for the shear strength parameter ϕ'.

New Failure Criterion.--For the consolidated-undrained tests on high fiber content samples excess pore water pressures tended to reduce the minor principal effective stress, σ_3', to zero at axial strains of 15+ percent. For the limiting condition, $\sigma_3' \rightarrow 0$, the shear strength parameter ϕ' must approach 90 degrees. This would appear to be an unrealistic value. To avoid this problem, data for consolidated-undrained triaxial tests have been presented with failure based on the maxium ratio of shear stress to effective normal stress (maximum obliquity) as shown in Figure 6. The failure envelope passes through the origin and is tangent to the respective failure circles. Data points shown by diamonds correspond to 40% fiber/60% kaolinite (dry weight basis) samples and the triangles represent papermill sludge with close to the same fiber content. Data points showing development of the $(\tau/\sigma')_{max}$ ratio have been included for samples CU-CF3 and U-1-13 where the ratio represents the maximum obliquity for the given axial strain. For kaolinite this criterion gives the same ϕ' for both consolidated-undrained or -drained conditions. At fiber contents of about 25+% (dry weight basis) this new failure criterion avoids the problem where the minor effective principal stress may approach zero. Values for the shear strength parameter ϕ' ranged from 20 degrees for kaolinite up to 39 degrees for all fiber samples as shown in Figure 5.

Field Application.--The question remained as to which shear strength parameter in Figure 5 would be suitable for application to field problems. Field data for failure in an excavated slope in consolidated fibrous papermill sludge with properties very similar to the fiber/kaolinite mixtures have been reported by Charlie (1975). The slope cross-section, piezometer locations, and pore water pressures are given in Figure 7. Tabulated values for the slope stability analysis using Janbu's method (1954, 1957) are given in Table 1. The stability analysis, effective stress basis, required that pore water pressures be extrapolated to the failure surface. Water retention characteristics for the fibrous sludge (Laza, 1971) indicated that pore pressures at the excavation surface would be negative, i.e. water would be absorbed. This fact was used in estimating the pore pressure variations

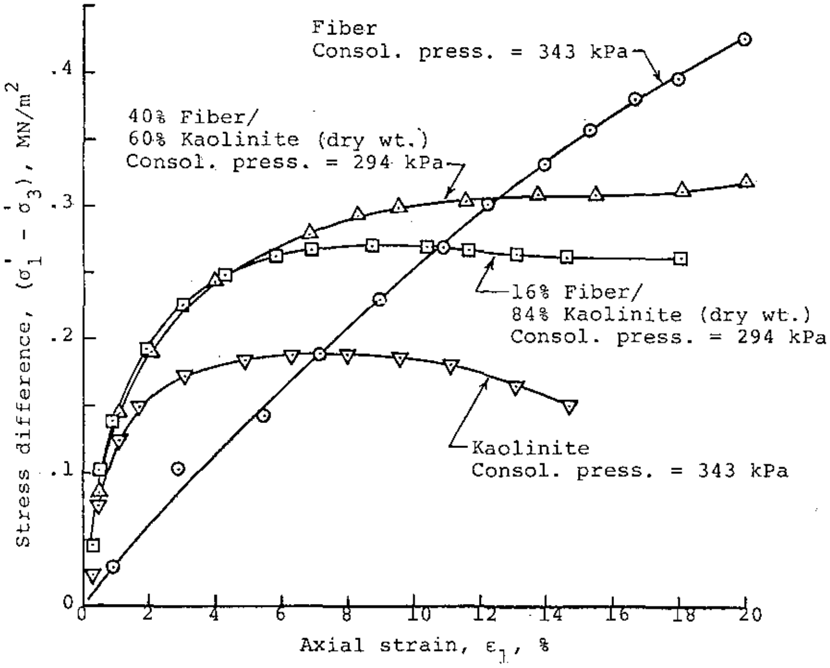

Figure 3. Stress-strain curves for undrained conditions and samples with different kaolinite/fiber combinations.

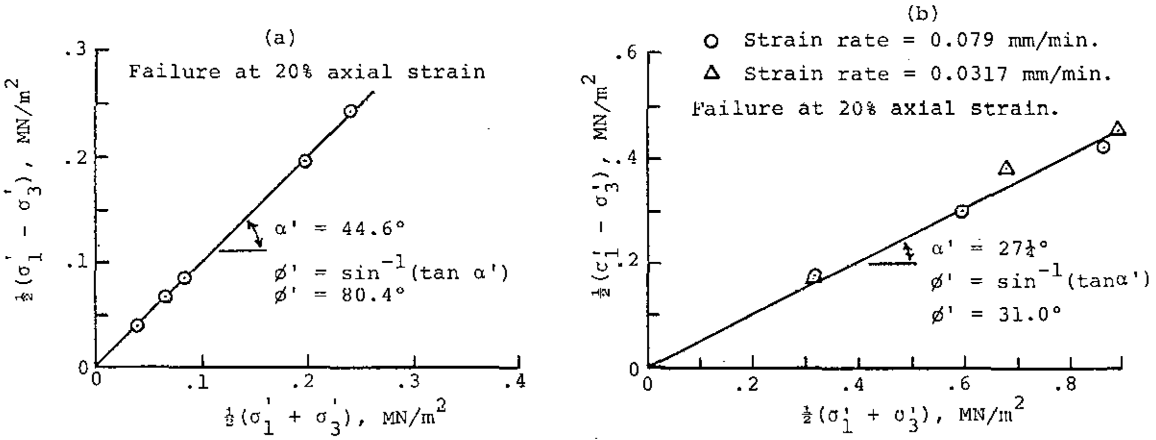

Figure 4. Summary of triaxial data for fiber samples. (a) Consolidated-undrained tests. (b) Consolidated-drained tests.

(dashed curves) shown in Figure 7c. The fiber content of the sludge was close to 57% (dry weight basis), hence three possible ø' values for the fiber/kaolinite soil mixtures are shown in Figure 5. The higher value of ø' equal to 52 degrees gave a computed factor of safety close to unity (Table 1). Lower values of ø' would give a lower safety factor thus eliminating from consideration ø' values from the drained test and the new failure criterion. The consolidated-undrained triaxial test gave the ø' value in best agreement with field behavior of the observed slope failure.

CONCLUSIONS

1. The addition of small amounts of fiber significantly increased the peak strength of kaolinite for undrained loading conditions. Larger amounts of fiber changed the material behavior from brittle to plastic with strength continuing to increase up to 20+% axial strain.

2. Shear strength of the fiber/kaolinite mixtures increased with normal stress suggesting a frictional type behavior in accordance with the principal of effective stress. The shear strength parameter ø' was dependent on both the fiber content of the soil mixtures and the test procedure.

3. Consolidated-drained triaxial test with failure based on the peak stress or stress at 20% axial strain gave ø' values which increased from 20 degrees for kaolinite up to 31 degrees for all fiber samples. Consolidated-undrained tests with the same failure conditions gave ø' values ranging from 20 degrees for kaolinite to 80.4 degrees for all fiber samples.

4. A new failure criterion for the consolidated undrained tests gave intermediate values of ø' ranging from 20 degrees for kaolinite up to 39 degrees for all fiber samples. This method avoids the tendency for the minor principal effective stress to approach zero for undrained loading conditions with high fiber content samples and axial strains of about 15+%.

5. Recomputation of the safety factor for an experimental slope failure in an excavated fibrous sludge with properties similar to the fiber/kaolinite mixtures suggests that the shear strength parameter ø' based on consolidated-undrained tests is the most suitable for a stability analysis. Use of ø' from consolidated-drained tests gave val-

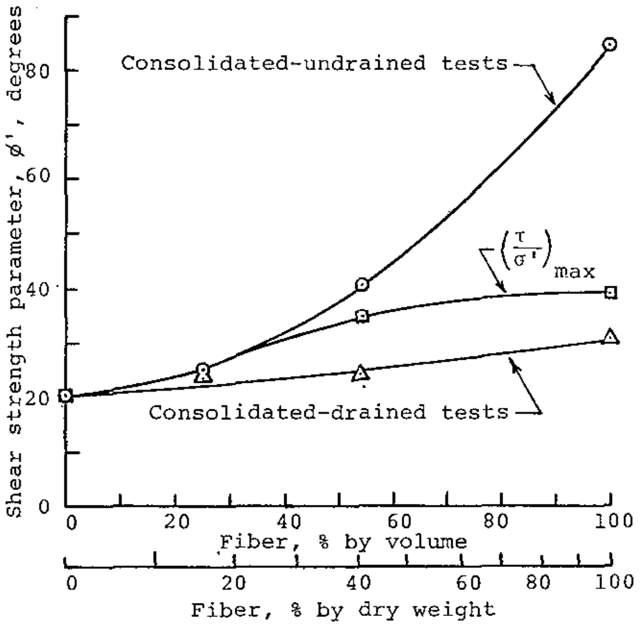

Figure 5. Fiber content versus shear strength parameter ø' for kaolinite/fiber mixtures.

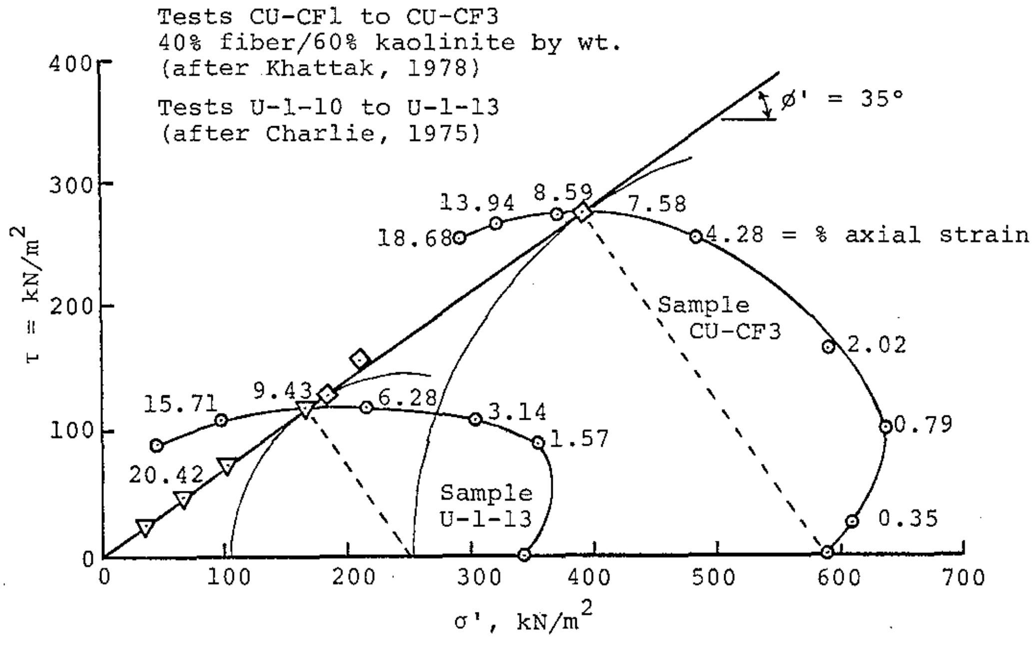

Figure 6. Consolidated-undrained triaxial data presented in terms of the maximum ratio of shear stress to effective normal stress (maximum obliquity).

ues for the factor of safety much less than unity.

ACKNOWLEDGEMENT

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REFERENCES

1. Bishop, A.W., and Henkel, D.J.: The Measurement of Soil Properties in the Triaxial Test. Edward Arnold (Publishers) Ltd., London, 2nd ed., 1962.
2. Charlie, W. A.: Two Cut Slopes in Fibrous Organic Soils, Behavior and Analysis. unpublished Ph.D. thesis, Michigan State University, East Lansing, Michigan, 1975.
3. Janbu, N.: Earth Pressure and Bearing Capacity Calculations by Generalized Procedure of Slices. Proc. 4th International Conf. on Soil Mechanics and Foundation Engineering, London, II:207-212, 1957.
4. Janbu, N.: Discussion on Application of Composite Slip Surfaces for Stability Analyses. European Conf. on Stability of Slopes Stockholm, III:43-49, 1954.
5. Khattak, Anwar S.: Mechanical Behavior of Fibrous Organic Soils. unpublished Ph.D. thesis, Michigan State University, East Lansing, Michigan, 1978.
6. Laza, R.W.: Permeability and Shear Strength of Dewatered, High Ash Content Pulp and Papermill Sludges. unpublished Ph.D. thesis, Michigan State University, East Lansing, Michigan, 1971.
7. Perkin-Elmer Corporation: Instruction Manual of Perkin-Elmer Shell Model 212B Sorptometer. Instrument Division, Norwalk, Connecticut, 1961.
8. TAPPI: Fiber Length of Pulp By Classification, Suggested Method T 233 su-64. Technical Association of the Pulp and Paper Industry, Atlanta, Georgia, 1964.

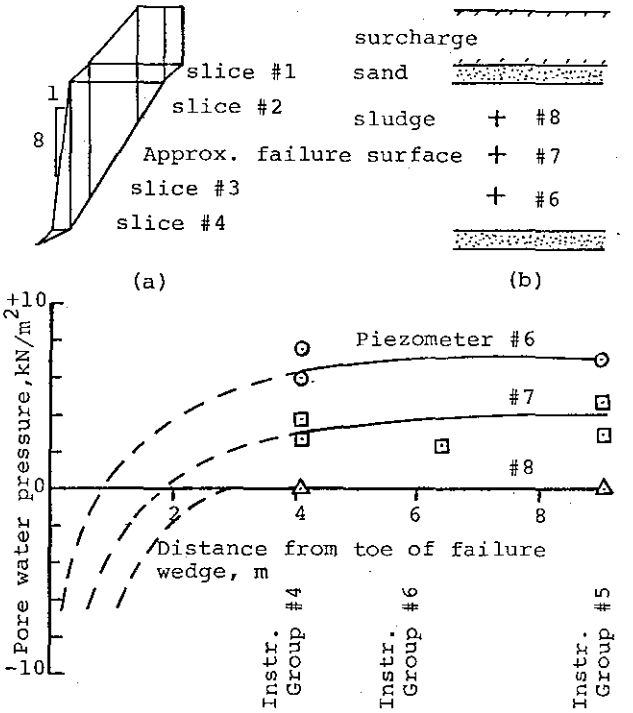

Figure 7. Slope failure in consolidated fibrous papermill sludge (Charlie, 1975). (a) Slope cross-section. (b) Piezometer elevations. (c) Pore water pressures.

Table 1. Slope stability analysis using Janbu's method (1954, 1957)

Slice No	$^c\tan\alpha$	$^c\Delta x$ (m)	$^c p$ $(\frac{kN}{m^2})$	$^a\Delta U$ $(\frac{kN}{m^2})$	ϕ' (deg)	p' $(\frac{kN}{m^2})$	B_o	A'_o	n_α	A_o
1	1.00	0.305	21.125	0	39	21.125	6.443	5.217	0.971	5.373
2	1.64	0.457	27.794	-2.413	^{b}52	30.207	20.831	17.669	0.933	18.938
3	1.64	0.762	29.829	-2.413	^{b}52	32.242	37.277	31.446	0.933	33.704
4	1.64	0.305	28.048	-1.724	^{b}52	29.772	14.030	11.622	0.933	12.457
5	0.50	0.305	15.451	0	39	15.451	2.356	3.816	1.177	3.242
6	0.50	0.305	1.197	0	39	1.197	0.183	0.296	1.177	0.251
							Σ=81.120	Σ=70.066		73.965

Notes: [a]Pore pressures from Figure 7.

[b]Shear strength parameter ϕ' from Figure 5 for an average fiber content ≈ 57% (dry weight basis).

[c]Tanα, Δx, and p for all slices and ϕ' for slices 1, 5, and 6 remain the same as given by Charlie (1975).

$B_o = p \tan\alpha \, (\Delta x)$, $A'_o = p' \tan\phi' \, (\Delta x)$, $A_o = \frac{A'_o}{n_\alpha}$, $n_\alpha = \cos^2 \alpha (1 + \frac{\tan\alpha \tan\phi'}{F})$.

Table complete only for $F_o = \frac{\Sigma A_o}{\Sigma B_o} = \frac{73.965}{81.120} = 0.91$

Additional calculations give $F_2 = \frac{\Sigma A_o}{\Sigma B_2} = \frac{74.0}{79.8} = 0.93$ for a line of thrust for side forces on each slice through the lower $\frac{1}{3}$ points.