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Water content changes along shear planes in drained and undrained triaxial compression tests on unsaturated cohesive soils

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Abstract

Drained and undrained triaxial compression tests were run on undisturbed samples of two unsaturated cohesive soils to study water content changes in drained and undrained conditions along shear planes. The results show that while there is a noticeable water content increase away from the failure planes in the undrained tests, there seems to be an insignificant water content change in the drained tests.

Key Words: Water content, drained and undrained shear, triaxial compression tests, failure plane, unsaturated soils, cohesive soils

Suya doygun olmayan kohezyonlu zeminlere uygulanan drenajlı ve drenajsız üç eksenli basınç deneylerinde kayma düzlemi boyunca oluşan su içeriği değişimleri

Özet

Drenajlı ve drenajsız koşullarda kayma düzlemi boyunca oluşan su içeriği değişimlerini incelenmek için suya doygun olmayan iki kohezyonlu zeminden alınan örselenmemiş numuneler üzerinde drenajlı ve drenajsız üç eksenli basınç deneyleri yapılmıştır. Sonuçlar drenajsız deneylerde kırılma düzleminden uzaklaştıkça su içeriğinin arttığını gösterirken, drenajlı deneylerde kayma düzlemi boyunca su içeriğinin belirgin bir şekilde değişmediğini göstermiştir.

Anahtar Sözcükler: Su içeriği, drenajlı ve drenajsız kesme, üç eksenli basınç deneyi, yenilme düzlemi, suya doygun olmayan zeminler, kohezyonlu zeminler

Introduction

Studies show that the shear strength of a cohesive soil generally increases as the rate of shear is increased. Casagrande and Shannon (1948a) found from undrained tests that the strength of a very soft organic clay when sheared in 1.7 minutes was 40% greater than the strength of the same clay when sheared in 7 hours. Several clays, when they failed in dynamic tests (in which only 0.02 seconds elapsed between the start of shear and the attainment of maximum compressive stress), showed strengths 1.4 to 2.6 times those obtained with a 10-minute loading time and 1.4 to 3.2 times those obtained with a 4-hour loading time (Casagrande and Shannon, 1948b) and the same is true for direct shear tests (Lambe, 1951). Olson and Parola (1967) report a compressive strength increase of 18% for the range of 60 milliseconds to 6 milliseconds for a clay compacted near optimum moisture content . Similar to Ward et al.

(1959), Simons (1965), Tchalenko (1967) and Esu and Calabresi (1969), Cetin (1997) conducted standard consolidation tests using Casagrande (1936) construction method, and determined vertical and horizontal preconsolidation stresses and in turn, the failure envelopes for two unsaturated cohesive soils, namely B and C, along an active fault in Oklahoma, USA. Because the failure envelopes are above the failure envelopes needed for slow (drained) failure of the same soils, he concluded that the faulting of these soils was probably caused by sudden or fast slip on the fault (under undrained conditions). Comparing the two failure envelopes, he reported a 40% increase in effective shear stress in the soil unit B and 70% in the soil unit C (Table 1).

Table 1. Relationship between shear strength and shear rate or failure time.

Shear Strength Increase (%)	Failure Time	Reference
140-260	0.02s - 10 min	Casagrande and Shannon, 1948b
140-320	0.02s - 4 hr	Casagrande and Shannon, 1948a
40	1.7 min - 7 hr	Casagrande and Shannon, 1948b
40-70	0.1-0.3ms -2-3d	Cetin, 1997

Any force will cause approximately twice as much stress and deformation when applied suddenly as when applied progressively, but because the stress conditions are complex and depend upon the properties of the material as well as upon the nature of the load, truly sudden loading is very hard to secure (Roark, 1954). Most of the complexity comes from the unequalization of pore pressures throughout the specimen at failure (ASTM D 4767-88, 1993).

This increase in shear strength is because of the fact that during shear, effective stress increases as the rate of shear increases (Henkel, 1960; Kulhawy and Mayne, 1990; Mitchell, 1993) and pore water moves away from the plane of shear (Taylor, 1951; Bishop and Henkel, 1953; Crawford, 1961). For this reason, effective failure envelopes for undrained tests are above the effective failure envelopes for drained tests (Casagrande and Wilson, 1953; Hirschfeld, 1960).

Taylor (1951), Bishop and Henkel (1953) and Crawford (1961) studied water migration away from shear planes for saturated soils. But a significant portion of the earth's surface is subjected to arid and semiarid climatic conditions, and as a result, many of the soils encountered in engineering practice are unsaturated or partially saturated (Fredlund and Rahardjo, 1993). Therefore, the aim of this study was to study water migration along shear planes under drained and undrained conditions for unsaturated or partially saturated cohesive soils.

1. Materials and Methodology

Thirty-tree triaxial and nine unconfined compression tests were performed on undisturbed samples from the two cohesive soils (Soil B and C) of Cetin (1997). The tests were run in general accordance with the American Society for Testing Materials (ASTM D 4767-88 and ASTM D 2166-91) (1993), respectively. Samples were taken according to ASTM D 1587-83 (1993) specifications. They were wrapped tightly in aluminum foil and then coated with wax, cheesecloth, and again wax layers in the field as soon as they were extruded, to retain their natural field moisture contents. Some of the properties of the soils are given in Table 2.

As soon as failure was accomplished, the tests were stopped, and the samples were removed as quickly as possible from the triaxial chamber and divided into five slices parallel to the failure plane in order to measure moisture content variation between slices. When the failure was accompanied by shear along a well-defined plane, the shear plane was included in the middle slice (slice 3). In few tests, the failure occurred as bulging or barreling. Then, the middle slice was taken diagonally making a 60° angle with the base (horizontal) of the sample assuming the failure plane would occur in this zone.

In addition to these tests, to study the water content in the samples after consolidation but before shearing, two samples (one from B, one from C) were consolidated under 20.59 and 41.19 kpa representing the maximum sampling depths of 2.4 and 5.5 m, respectively, for 24 h and then removed from the cell quickly without shearing. End slices were removed and the specimens were divided into upper, middle, and lower sections. Each section was trimmed concentrically into an outer, intermediate, and central portion. Water contents of each portion were determined.

The test apparatus consisted of a triaxial cell (Model 1020), a loading frame (Model T-56-B), a pressure board (Model 1277), a pressure chamber (Model 13000), made by Wykeham Farrance and a data acquisition system.

Table 2. Properties of the soils

Soil Properties	Soil	
	B	C
Depth (m)	0-2.4	0-5.5
Elevation (m)	386.0-383.6	383.6-378.1
Natural water content (%)	5.0-21.0	5.0-33.0
Liquid limit (%)	31.0	33.0
Plastic limit (%)	18.7	17.7
Shrikage limit (%)	15.5	13.8
Plasticity index (%)	12.4	15.3
Specific gravity	2.70	2.72
Grain sizes (%)		
Gravel	1.0	1.0
Sand	30.0	38.0
Silt	31.0	23.0
Clay	38.0	38.0
Soil type (USCS)	CL	CL
Name	Silty clay	Sandy clay
Preconsolidation press. (kpa)	107.88	117.68

2. Results and Discussion

Test results are summarized in Table 3 and the average variations are shown in Figures 1 and 2. The average water contents of the slices in the undrained tests were 15.27 % for soil B and 17.20 % for soil C. The average water contents of the slices enclosing the failure planes were 15.10 % and 16.58 %, respectively. The water contents decreased consistently toward the failure planes averaging 15.19 % and 15.10 %, and 17.35 % and 17.26 % at the extremities to 15.10 % and 16.58 % at the failure plane, respectively. There was a noticeable water movement away from the failure planes during undrained triaxial shear tests (Figure 2). The difference between the average water content for the five slices and the slice enclosing the failure plane was 0.17 % for soil B and 0.62 for soil C. Taylor (1951) and Crawford (1961) measured 1.5 % and 1.2 % variations in water content for saturated cohesive soils, respectively.

The two tests run to study water content before shear and after consolidation revealed a pattern of water content that suggests different degrees of consolidation throughout the specimen. The tests show the outer shell to have been about 0.70-0.80 % dryer than the central portions (Figures 2 and 3). The slice 3s from sheared specimens were from the inner portion of the sample, while the slices 1s and 5s came from the outer shell, and it is therefore reasoned that slice 3 was wetter than average before shearing. Since it was dryer than average after shearing, this suggests an even greater movement of water during shear than is indicated by measurements on slices parallel to the failure plane. This water movement may have been due to stress concentration, microcracks opening and increasing connectivity near the failure plane before the failure, driving the water away from it.

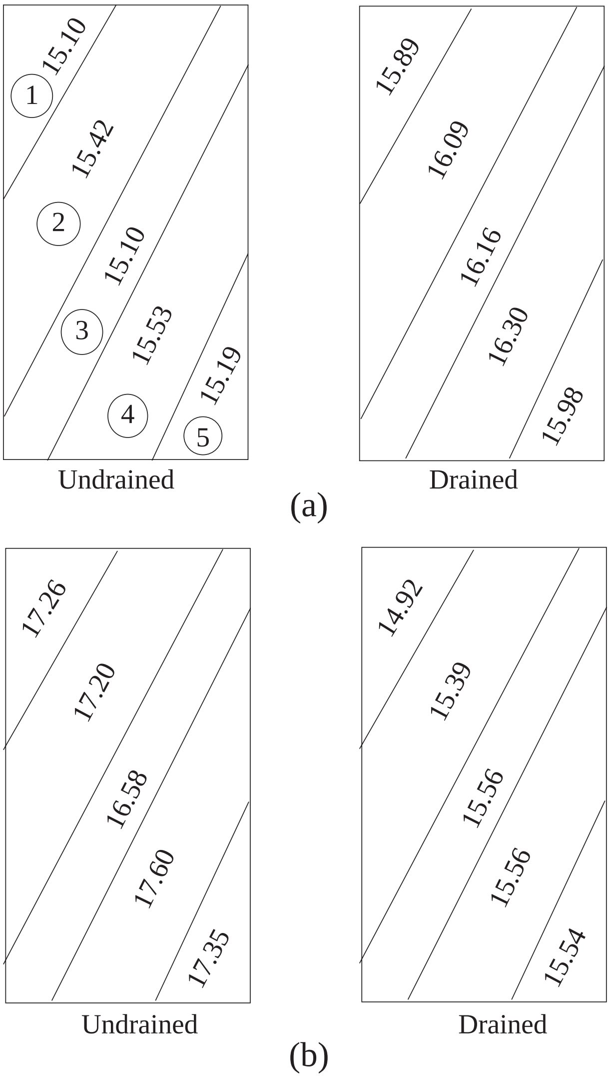

Figure 1. Average water contents of slices 1, 2, 3, 4, and 5 for the soils (a) B and (b) C after undrained and drained triaxial compression tests.

Table 3. Summary of the test results

Soil	Specimen No	Test Type†	Confining Pressure (kpa)	Deviatoric Stress (kpa)	Shear Rate (cm/min)	Average Water Content (%)		Water Content of Slices (%)					Initial Degree of Saturation (%)
						Initial	Failure	1	2	3	4	5	
B	1	CU	102.97	237.33	74.06640	14.21	13.61	13.83	13.76	13.11	13.59	13.77	50.14
	2	UUC	0	56.88	0.15240	16.06	15.96	16.21	16.25	16.15	15.71	15.50	61.61
	3	UUC	0	72.57	1.36250	16.47	16.18	16.28	16.28	15.85	16.24	16.24	69.37
	4	CU	102.97	448.18	37.55140	11.61	10.81	10.08	11.11	10.11	11.15	11.59	45.11
	5	CU	20.59	141.22	51.12000	16.26	15.68	15.79	15.65	15.35	15.77	15.85	66.33
	6	CU	20.59	159.85	1.49000	16.84	16.27	16.68	16.71	16.09	16.36	15.52	76.20
	7	CU	20.59	167.70	1.55000	17.10	16.80	16.29	16.88	16.76	17.13	16.94	73.87
	8	CU	20.59	186.33	74.06640	18.11	17.09	15.76	17.64	17.15	17.39	17.53	80.90
	9	CU	20.59	182.41	50.89140	17.34	16.24	15.57	16.40	16.05	16.64	16.52	70.08
	10	CU	20.59	179.47	74.06640	18.55	17.25	17.06	17.67	17.32	17.21	16.98	66.83
	11	CU	20.59	241.25	1.65280	12.77	12.10	12.93	12.07	11.84	11.96	11.70	47.41
	12	UUC	0	83.36	1.05210	15.60	15.21	15.81	15.89	15.39	15.91	13.07	72.51
Averages							**15.27**	**15.19**	**15.53**	**15.10**	**15.42**	**15.10**	**65.03**
	13	UDC	0	63.75	0.00031	16.41	15.69	15.40	15.40	15.83	15.91	15.91	71.28
	14	CD	20.59	114.74	0.00031	20.96	19.57	20.10	20.07	19.46	19.26	18.94	68.59
	15	CD	20.59	132.39	0.00031	18.03	16.46	15.87	16.76	16.87	16.59	16.20	66.41
	16	CD	20.59	100.03	0.00031	18.77	17.69	17.44	18.26	17.17	17.99	17.57	71.28
	17	CD	20.59	263.81	0.00031	12.33	11.01	11.07	10.99	11.46	10.70	10.84	45.32
Averages							**16.08**	**15.98**	**16.30**	**16.16**	**16.09**	**15.89**	**64.58**

† Test Type:
CU:Consolidated undrained
CD: Consolidated drained
UUC: Unconfined undrained compression
UDC: Unconfined drained compression

Table 3. Continued

Soil	Specimen No	Test Type†	Confining Pressure (kpa)	Deviatoric Stress (kpa)	Shear Rate (cm/min)	Average Water Content (%)		Water Content of Slices (%)					Initial Degree of Saturation (%)
						Initial	Failure	1	2	3	4	5	
C	1	CU	102.97	162.80	0.11430	19.84	19.55	20.70	19.58	19.11	19.21	19.17	74.46
	2	CU	102.97	546.25	1.45240	11.91	11.79	12.88	11.65	11.54	11.11	11.78	50.40
	3	CU	102.97	311.86	75.12560	12.80	12.52	13.26	-	11.58	13.04	12.21	46.39
	4	CU	102.97	171.62	74.90460	20.42	19.98	18.16	18.27	19.19	21.81	22.48	78.50
	5	UUC	0	52.96	0.15240	19.81	19.67	21.01	21.09	17.22	20.54	18.49	75.54
	6	UUC	0	46.09	1.33650	19.02	18.84	19.67	19.95	17.48	17.82	19.26	76.75
	7	UUC	0	211.83	1.35810	18.74	18.38	18.33	18.64	18.25	18.37	18.30	82.67
	8	CU	41.19	213.79	50.36820	17.54	17.17	15.96	17.20	17.15	17.91	17.61	78.57
	9	CU	41.19	112.78	1.67100	20.37	19.97	20.32	19.97	19.51	19.54	20.51	77.34
	10	CU	41.19	138.28	50.36820	20.55	19.11	21.96	20.54	17.63	17.89	17.52	78.80
	11	CU	41.19	225.56	1.65840	16.81	16.62	18.35	17.31	16.53	15.73	15.20	79.94
	12	CU	41.19	195.16	1.68940	15.11	14.91	14.26	14.71	14.73	15.18	15.65	49.64
	13	CU	41.19	117.68	50.36820	20.71	19.42	19.09	18.80	18.87	19.82	20.51	68.22
	14	CU	41.19	68.65	50.36820	22.72	20.76	20.71	20.89	20.72	20.58	20.90	70.72
	15	CU	41.19	272.63	51.66360	18.91	17.67	18.34	18.57	17.71	16.86	16.86	75.20
	16	CU	41.19	486.43	1.39980	14.25	13.78	11.94	13.09	13.48	15.14	15.24	60.90
	17	CU	41.19	823.79	1.43870	12.53	11.21	10.02	11.30	11.24	11.77	11.71	54.90
Averages							**17.20**	**17.35**	**17.60**	**16.58**	**17.20**	**17.26**	**69.35**
	18	CD	102.97	237.33	0.00061	19.35	15.78	16.35	16.09	16.73	15.46	14.26	72.62
	19	CD	102.97	504.08	0.00061	14.05	11.73	13.10	13.06	12.56	10.36	9.57	36.14
	20	UDC	0	76.49	0.00031	20.57	17.46	17.40	18.12	17.96	17.04	16.78	73.23
	21	UDC	0	34.32	0.00031	20.76	18.71	20.15	18.69	18.01	18.65	18.04	76.50
	22	CD	41.19	87.28	0.00031	21.02	19.59	21.51	20.08	18.92	19.23	18.20	69.85
	23	CD	41.19	124.55	0.00031	19.07	17.18	17.98	17.54	17.20	17.09	16.07	79.51
	24	CD	41.19	629.61	0.00031	15.22	12.68	10.48	12.76	13.19	13.58	13.40	63.43
	25	CD	41.19	965.99	0.00031	11.36	10.02	7.38	8.16	9.87	11.70	13.00	38.35
Averages							**15.39**	**15.54**	**15.56**	**15.56**	**15.39**	**14.92**	**63.70**

There was, however, little moisture content difference between the middle slice and the neighboring slices when the tests were drained (Figures 1 and 2). The average water contents of the slices enclosing the failure planes were 16.16 % and 15.56 % for soils B and C, respectively. The average water contents in the neighboring slices were 16.09 % and 16.30 %, and 15.39 % and 15.56 %, respectively. The average water contents at the extremities were 15.89 % and 15.98 %, and 14.92 % and 15.54 %. This may be because during drained tests there is enough time for water to equilibrate.

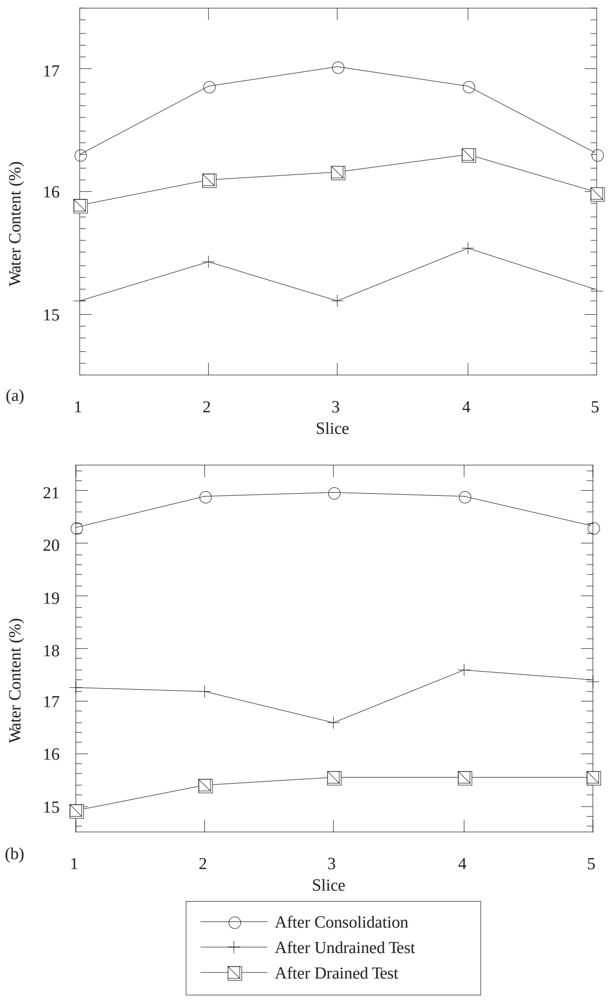

Figure 2. Water content variations after consolidation and drained and undrained triaxial compression tests. (a) soil B, (b) soil C.

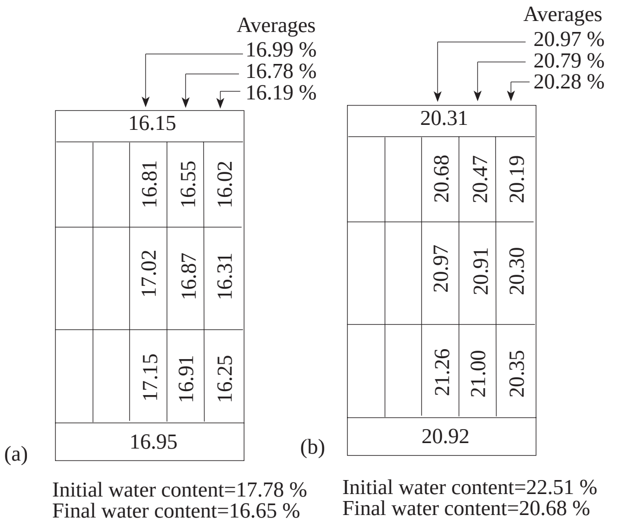

Figure 3. Water content variation after triaxial consolidation before shearing for the soils (a) B and (b) C.

After all undrained, drained, and the two triaxial consolidation tests, moisture contents of the upper parts of the samples were always less than the moisture contents of the lower parts also suggesting a downward water movement (Figures 1 and 2).

3. Conclusions

While pore water moves away from the plane of shear in unsaturated or partially saturated cohesive soils under undrained conditions there seems to be not much water movement under drained conditions. This may be one of the reasons why effective stress increases as the rate of shear increases. Also, there seems to be a downward water movement causing differences between the water contents of the upper parts and the lower parts. The water contents of the lower parts are always higher.

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