APPENDIX XB:

DETERMINATION OF CRITICAL VOID RATIO

1. **DEFINITION OF CRITICAL VOID RATIO.** Critical void ratio is that void ratio at which a cohesionless soil can undergo deformation or actual flow without volume change. In general, it is a function of confining pressure, i.e., an increase in confining pressure yields a lower value of critical void ratio. Theoretically, a soil with a void ratio above the critical value for the confining pressure is subject to flow failure or liquefaction if it undergoes sufficient undrained stress, whether that stress is cyclic or monotonic (steadily increasing). However, if the void ratio is lower than the critical value for the given confining pressure, the soil will not liquefy under monotonic stress increase. Liquefaction resulting from monotonic stress increase and "initial liquefaction" occurring under cyclic stresses are not the same phenomenon. For the purposes of this appendix, liquefaction refers to the behavior of a mass of cohesionless soil during flow slides. For monotonic loading conditions, failure is caused by a substantial reduction in shear strength due to large increases in pore pressure and the consequent great reduction of effective stress.

2. **PRINCIPLES OF MONOTONIC TRIAXIAL TESTING.** The monotonic stress-controlled triaxial compression test is used to determine the approximate values of critical void ratio over an applicable range of confining pressure. The test is comparable to an R test with pore pressure measurements (see Appendix X, TRIAXIAL COMPRESSION TESTS) with the exception that load is applied to the specimen in increments. The increments are arbitrary but should be chosen to produce several points on the stress-strain curve prior to peak deviator stress or the tendency to dilate, depending on the response of the

specimen as outlined below. The ability to execute an efficient test program to establish critical void ratio over a range of confining pressures requires recognition of the nature of specimen behavior. In general, three types of response from specimens can be anticipated, as illustrated in Figure 1.

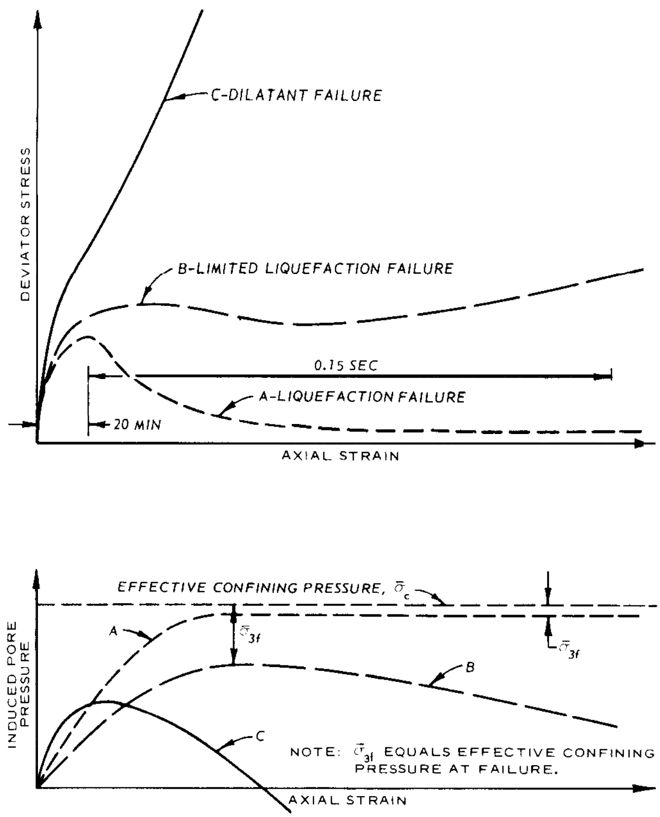

Figure 1. Typical stress-strain and pore pressure response, monotonic triaxial $\bar{R}$ tests on sands

a. Complete Liquefaction. If the void ratio after consolidation is sufficiently higher than the critical value for the given confining pressure, the specimen will bear several load increments with minor axial strain (usually less than 2 percent) while exhibiting steadily accelerating pore pressure increases until failure by liquefaction occurs catastrophically at peak deviator stress. During the collapse of the specimen, which occurs over a fraction of a second, the deviator stress actually borne by the specimen declines rapidly while the pore pressure approaches, but not necessarily equals, the confining pressure.

b. Partial or Limited Liquefaction. If the void ratio after consolidation is slightly higher than or very nearly equal to the critical value for the given confining pressure, the specimen will tolerate several load increments with small axial strain until at peak deviator stress sustained deformation will occur. The deviator stress will essentially remain constant or suffer minor decline during the deformation. In some cases, deformation will cease, but the addition of small increments of load that counter the effects of area increase due to strain will maintain deformation. During the deformation, the pore pressure will rise to a value somewhat less than the confining pressure. In the latter stages of the test, the specimen response may become dilative, i.e., it will bear additional deviator stress, and the pore pressure will begin to decrease.

c. Dilatant Failure. If the void ratio after consolidation is lower than the critical value for the given confining pressure, the specimen will tend to dilate, i.e. continue to accept loading, and the pore pressure decreases.

3. APPARATUS. All the equipment is listed in Appendix X, TRIAXIAL COMPRESSION TESTS, for performing triaxial compression R tests with pore pressure measurements plus (a) electronic transducers and high-speed recorders for data acquisition, and (b) stress-controlled loading capacity.

a. Loading Devices. The equipment may be either (1) a pneumatic system, (2) a closed-loop electrohydraulic system, or (3) a deadweight system. A deadweight system is practical only for 1.4-in.-diameter specimens. Such small specimens may be used, but they are undesirable from the standpoint of specimen preparation (see Appendix X, TRIAXIAL COMPRESSION TESTS, pp X-15 and X-16). Figure 2 shows a satisfactory arrangement for deadweight loading, which consists of a horizontal loading bar bearing on the load rod (piston) and connected to a weight hanger suspended beneath the triaxial chamber. A stopblock must be provided beneath the weight hanger that will permit deformation of the specimen equivalent to not less than 30 percent axial strain but will prevent contact of the horizontal loading bar with the top of the triaxial chamber. The loading assembly should be designed to support 300 lb and constructed of lightweight material. Pneumatic or closed-loop electrohydraulic systems must be capable of maintaining the axial load, i.e., supply sufficient air or oil to allow the piston to follow the sudden and rapid deformation during liquefaction.

b. Specimen Cap. The specimen cap should be of a lightweight noncorrosive material equipped with porous metal or porous stone inserts and drainage connections. The cap can be similar to those in Figure 4 of Appendix X, TRIAXIAL COMPRESSION TESTS, but lubricated end platens similar to those used by Castro† are more desirable. Preferable specimen diameter is 2.8 in. or larger.

c. Triaxial Compression Chamber. The chamber is the same as that in paragraph 3b of Appendix X, TRIAXIAL COMPRESSION TESTS, or the newer design shown in paragraph 3c of Appendix XA, CYCLIC TRIAXIAL TESTS, except that the rigid connection of the loading piston to specimen cap is not required.

d. Loading Piston to Loading Equipment Connection. See paragraph 3d of Appendix XA, CYCLIC TRIAXIAL TESTS.

e. Recording Equipment. See paragraph 3e of Appendix XA, CYCLIC TRIAXIAL TESTS.

---

† G. Castro, "Liquefaction of Sands," Harvard Soil Mechanics Series No. 81, Jan 1969, Cambridge, Mass.

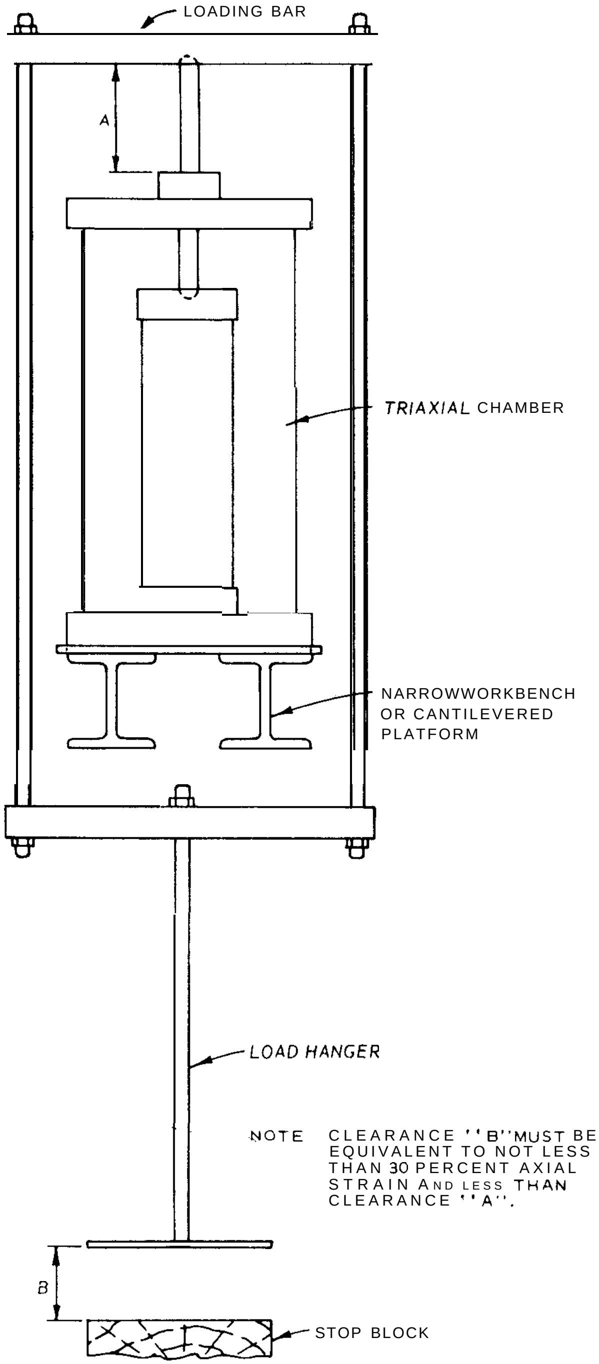

Figure 2. Deadweight loading system

f. Measurement Transducers. See paragraph 3f of Appendix XA, CYCLIC TRIAXIAL TESTS.

g. Back-Pressure Saturation Equipment. See paragraph 3g of Appendix XA, CYCLIC TRIAXIAL TESTS.

h. Tamping Rod for Moist Tamping Specimen Preparation. (Optional) See paragraph 3h of Appendix XA, CYCLIC TRIAXIAL TESTS.

4. TESTING PROCEDURES. Specimen preparation, back-pressure saturation, and consolidation procedures specified in paragraphs 4b and 7b(1) through 7b(7) of Appendix X, TRIAXIAL COMPRESSION TESTS, are adequate and pertinent. However, preferred techniques for handling undisturbed samples of cohesionless soils, preparing remolded specimens, and anisotropic consolidation are as follows:

a. Reconstituted Specimen Preparation (Moist Tamping). The procedure is as outlined in paragraph 4a of Appendix XA, CYCLIC TRIAXIAL TESTS, except that the initial water content of the material should be near the bulking water content, i.e., 5-10 percent. This water content permits molding of specimens in the vicinity of the critical void ratio, which is typically a relatively high value, i.e ., usually between 10 and 40 percent relative density, depending on the confining pressure.

b. Specimen Preparation (Undisturbed). See paragraph 4b of Appendix XA, CYCLIC TRIAXIAL TESTS.

c. Specimen Measurement. Inasmuch as void ratio is a principle of the test results, it is imperative that accurate initial specimen dimension measurements and volume change determinations during saturation and consolidation be made. Diameter measurements should be made to the nearest 0.001 in. using a circumferential tape†

† Commercially available from PI Tape, Box 398, Lemon Grove, Calif. 92045.

at the top, midheight, and bottom of the specimen or dial-gage calipers at the same locations, except two readings should be taken at each position by rotating the dial-gage calipers 90 deg to produce a total of six diameter readings. Care must be taken not to deform or disturb the relatively loose specimen during diameter measurements. Height measurements to the nearest 0.001 in. at four locations and weights to the nearest 0.1 g are recommended for 2.8-in.-diameter specimens. Record the data on the data sheet. (Plate XB-1).

d. Preliminary Seepage Saturation. See paragraph 4d of Appendix XA, CYCLIC TRIAXIAL TESTS.

e. Consolidation. See paragraph 4e of Appendix XA, CYCLIC TRIAXIAL TESTS.

f. Monotonic Loading. If it does not already exist, a large air pocket should be formed at the top of the triaxial chamber by draining water† from the chamber but leaving enough water to cover the top of the specimen. The air pocket is required, so that the large rapid piston movements into the chamber at the onset of failure do not create chamber pressure fluctuations. The procedure is as follows:

(1) Record test number and specimen identification on recorder trace.

(2) Zero the recorder and transducer outputs, and record calibration steps and scale factors.

(3) Close valve F (D should have already been closed) as shown in Figure 16 of Appendix X, TRIAXIAL COMPRESSION TESTS.

(4) Initiate incremental axial loading using an increment

† Compressed air instead of water may be used as the confining medium provided saturation and consolidation procedures do not exceed 8 hr.

determined as described in (5) below. During loading, the chamber pressure is maintained constant, and the axial load, axial deformation, and change in pore water pressure are recorded with time. Slow recorder speeds can be used as long as the specimen is deforming slowly; manual recording of load, pore water pressure, and deformation can be made as long as specimen behavior permits (this practice can save time in data reduction in that recorder traces are troublesome to read). Loading is continued on approximately l-min intervals until either (a) the specimen liquefies or partially liquefies, or (b) the specimen tends to dilate. A complete stress-strain record, such as shown for liquefaction or limited liquefaction in Figure 1, is difficult to obtain and requires experience- However, it is achieved by increasing the recorder speed to 10 to 20 in. of record per second just as the specimen indicates impending failure. The clues to approaching rapid failure are an obvious increase in deformation rate and steadily accelerating increases in pore water pressure. If the specimen deforms steadily but not catastrophically, additional load increments may be applied as the straining tends to cease until the pore pressure begins to decline.

(5) The magnitude of the monotonic load increments is arbitrary but should be selected to provide several points on the stress-strain curve prior to peak deviator stress. For a confining pressure, $\overline{\sigma}_{3c}$, of 0.5 tsf, a reasonable increment would be equivalent to about 1.0 psi of deviator stress based on the initial area of the specimen. If the confining pressure is 5.0 tsf, an increment equivalent to about 5.0 psi is more practical. In any case, it is necessary to reduce the load increment as peak deviator stress is approached in order to prevent the application of the last increment from significantly exceeding the true peak value. Confident use of such a procedure must be learned through experience with initial tests on a given soil.

g. Specimen Removal. Following testing, the specimen should be carefully removed from the triaxial cell to make sure that no particles are lost, then dried and weighed for dry unit weight calculations.

5. COMPUTATIONS. a. From the initial specimen data recorded on the data sheet (Plate XB-1), compute the initial water content, initial void ratio, initial dry density, and if required, the initial relative density, using equations presented in Appendixes I, WATER CONTENT, and II, UNIT WEIGHTS, VOID RATIO, POROSITY, AND DEGREE OF SATURATION.

b. From saturation data, compute the values of Skempton's pore pressure parameter B, and record any specimen height changes during saturation, the static piston loads required to counterbalance uplift pressures, and the magnitude of applied back pressure. If the specimen has suffered a change in height during saturation, correct the initial volume assuming the initial area remains valid.

c. Record specimen dimension changes during consolidation, and compute the area of specimen after consolidation (A_c), dry density after consolidation (γ_d), and the void ratio after consolidation as follows or as indicated in Plate XB-1:

$$A_c = \frac{V_o - \Delta V}{H_o - \Delta H}$$

where,

V_o = initial volume of specimen, cc

ΔV = change in volume of water in specimen during consolidation, from burette reading

H_o = initial height of specimen, cm

ΔH = change in height during consolidation, cm

6. PRESENTATION OF RESULTS. The critical void ratio is estimated from a plot of void ratio after consolidation, e_c, versus the effective confining pressure at failure, $\bar{\sigma}_{3f}$, for specimens that exhibit complete or limited liquefaction. For specimens that exhibit complete

or limited liquefaction, $\bar{\sigma}_{3f}$ is taken as the difference between the consolidation confining pressure, $\bar{\sigma}_{3c}$, and the maximum pore water pressure generated during the test (see Figs. 1 and 3). Figure 4 illustrates construction of the critical void ratio, which is the approximate relationship between e_c and $\bar{\sigma}_{3f}$ for the range of σ_{3c} The most desirable test series includes two to three tests at each of several pertinent confining pressures, σ_{3c}; e.g., 0.5, 1.0, 2.0, 4.0, and 8.0 tsf. The objective is to build the specimens near the critical void ratio, but slightly above it, to obtain complete and limited liquefaction in failure. This can be accomplished by trial. A trial procedure is not wasteful since all tests are of value in establishing the critical void ratio relationship. It is suggested that a pilot test be performed with a specimen built to about 20 percent relative density and by applying a moderate consolidation stress (about 2 tsf). The behavior of this specimen should indicate the approximate position of critical void ratio. Smaller confining pressures would produce higher critical void ratios; and larger confining pressures, lower critical void ratios. Those specimens that tend to dilate upon loading serve to help fix a lower bound to the position of the e_c versus the $\bar{\sigma}_{3f}$ relationship.

7. POSSIBLE ERRORS. In addition to those described in paragraph 9 of Appendix X, TRIAXIAL COMPRESSION TESTS, the following are possible errors that would cause inaccuracies in the determination of critical void ratio.

a. Apparatus. (1) Loading system. Insufficient air or hydraulic fluid at failure conditions will cause unacceptable load reduction. Misalignment between the loading rod piston and load actuator or air piston may also cause unacceptable loading conditions.

(2) Electronic transducers and recording equipment. Improper calibration or sensitivity of the electronic transducers, incorrect balancing of amplifiers or zero settings, or improper range settings will result in inaccurate recording of actual loads, deformations, and

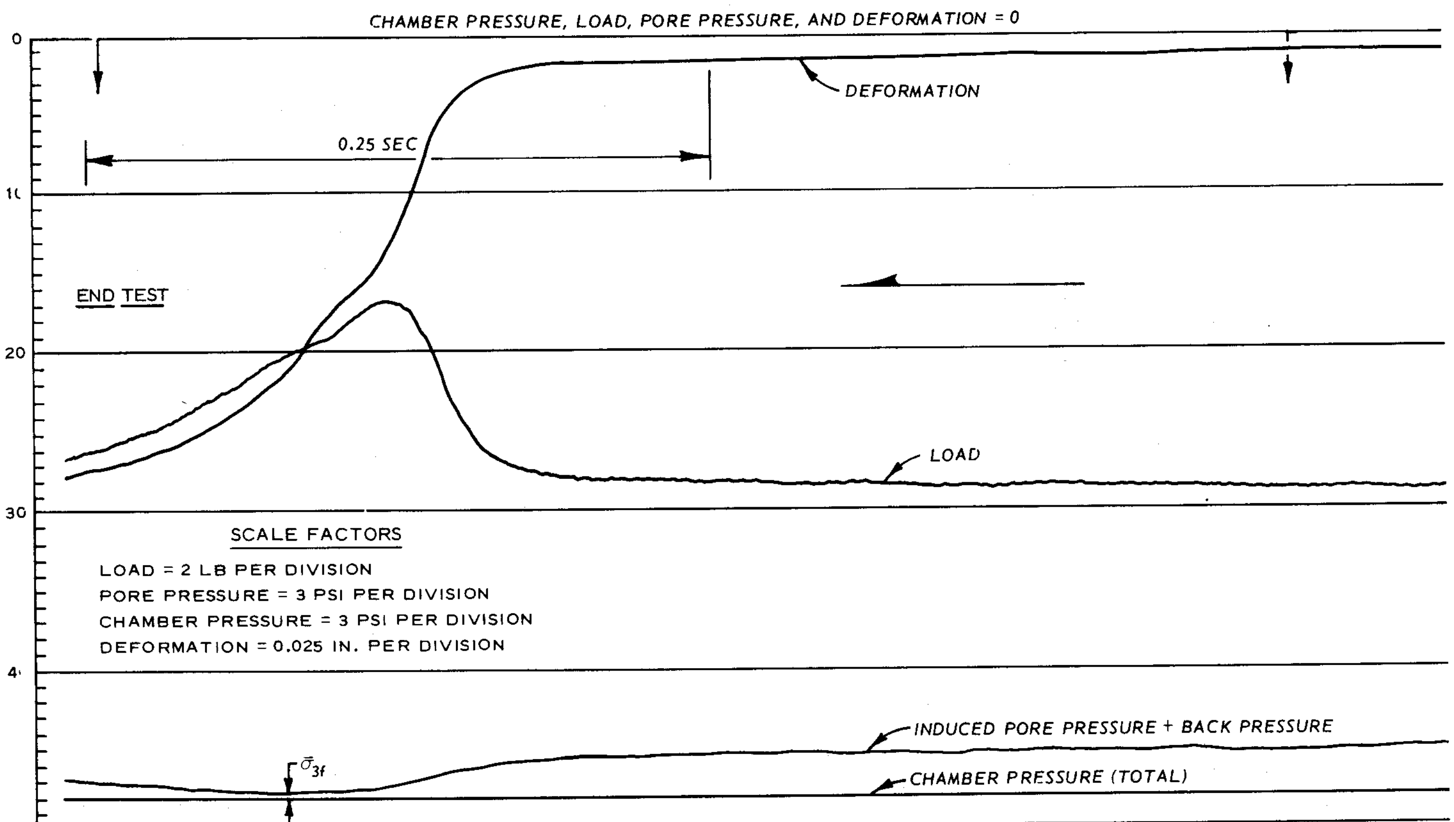

Figure 3. Facsimile of strip chart recorder readout for an anisotropically consolidated specimen that exhibited total liquefaction

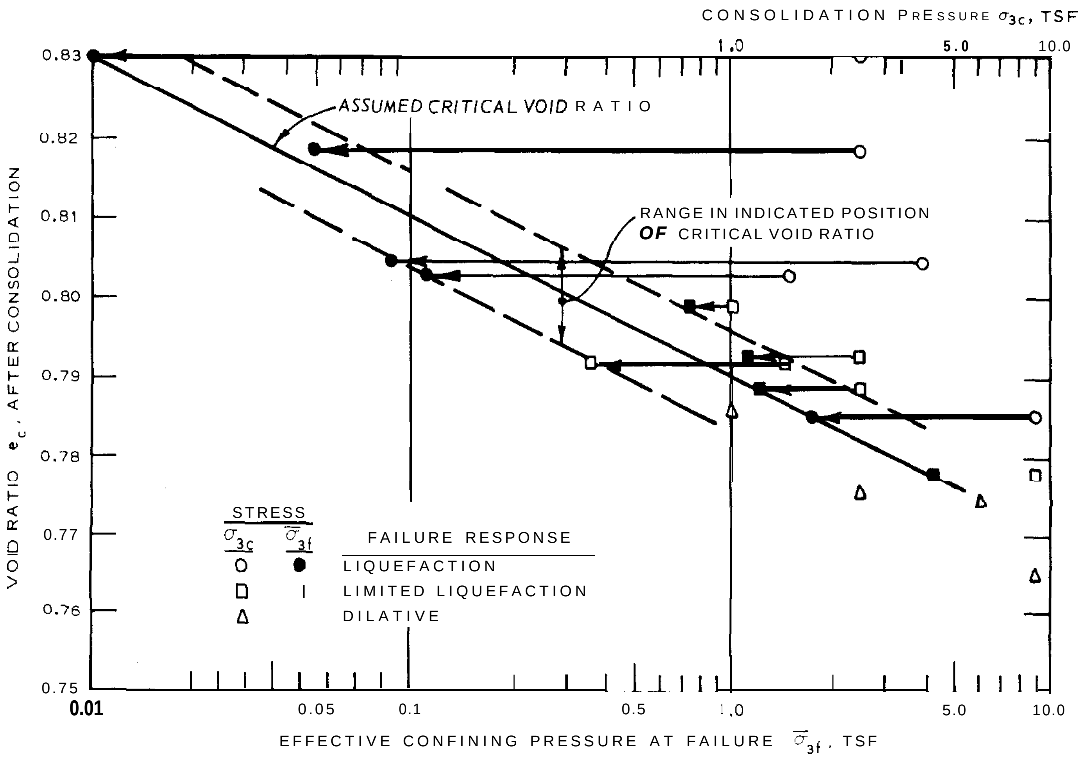

Figure 4. Example of the determination of approximate critical void ratio

pressures occurring during the test. It is also essential that the recorder response be rapid enough to follow all changes in the transducer output.

b. Specimen Preparation and Testing. (1) Specimen dimensions not measured precisely or density improperly calculated. A circumferential tape for measuring specimen diameter is recommended for obtaining precise measurements. Twice the thickness of the membrane must be subtracted for measurements of single membrane-encased specimens. An improperly calibrated burette will lead to incorrect volume change measurements during consolidation with resulting errors in specimen void ratio computations.

(2) Percent undercompaction in lower specimen layers improper for achieving desired average density.

(Uniform density in a reconstituted specimen is essential).

(3) Incomplete saturation resulting in low B values. The following problems can cause low B values: (a) use of insufficiently de-aired water may prevent dissolving of air in the specimen without resorting to extremely high back pressures; (b) incomplete de-airing or saturation of pore pressure transducer and drainage lines (can be avoided by applying a vacuum); and (c) system leaks due to punctured membrane, poor membrane sealing to cap and base, loose fittings, or improperly designed O-ring grooves (can be detected by using a bubble chamber while applying vacuum to the system).

(4) Assuming that the loading piston is not connected to the specimen cap, the static uplift load equal to the area of the loading piston multiplied by the chamber pressure must be accounted for when applying axial stresses.

(5) Scale factor for recorder traces not in agreement with actual data measurements. Reduction of data from recorder traces where scale factor, i.e., inches on recorder trace per pound (load), per inch (deformation), or per pounds per square inch (pressure), will result in data reduction error. The calibration steps should always be recorded on the recorder trace prior to and after testing.

MONTONIC TRIAXIAL COMPRESSION TEST (SPECIMEN DATA)	Date
Project	Boring No.
Specimen No. / Method of Specimen Preparation	

			Before Test			After Test	
			Specimen	Trimmings		Specimen	
Tare No.							
Weight, g	Tare plus wet soil						
	Tare plus dry soil						
	Water	W_w		W_{wo}		W_{wf}	
	Tare						
	Wet soil	W					
	Dry soil	W_s					
Water content		w	%	W_o	%	W_f	%

Initial Condition of Specimen

Membrane thickness, in.	T	Top	Center	Bottom	Avg
Diameter, in.		Top	Center	Bottom	Avg
Height, in.	H_o	North	East	South	West / Avg

Area, sq in. = $0.7854\ D_o^2$	A_o		Void ratio = $(V_o - V_s) \div V_s$	e_o	
Volume, cc = $16.39\ A_oH_o$	V_o		Saturation, %	S_o	
Specific gravity	G_s		Dry density, lb/cu ft	γ_d	
Volume of solids, cc	V_s		Relative density, %	D_d	

Saturation

Chamber Pressure σ_3, psi	Uplift Load P_u, lb	Chamber Pressure Change $\Delta\sigma_3$, psi	Back Pressure psi	Pore Pressure u, psi	Pore Pressure Change Δu, psi	B

$D_{avg} = \frac{D_{top} + D_{center} + D_{bottom}}{3} - 2T$ $B = \Delta u / \Delta \sigma_3$

$P_u = \sigma_3 \times A_{rod}$ - wt of piston

Condition of Specimen After Consolidation

Effective Confining Pressure After Consolidation, σ_c = ____________ tsf

Change in height during consolidation, in.	ΔH		Area, sq in. = V_c/H_c	A_c	
Height, in. = $H_o - \Delta H$	H_c		Void ratio = $(V_c - V_s) \div V_s$	e_c	
Change in volume, cc	ΔV		Dry density, lb/cu ft	γ_d	
Volume, cc = $V_o - \Delta V$	V_c		Relative density, %	D_d	

ENG FORM 4667 -R 1 APR 80