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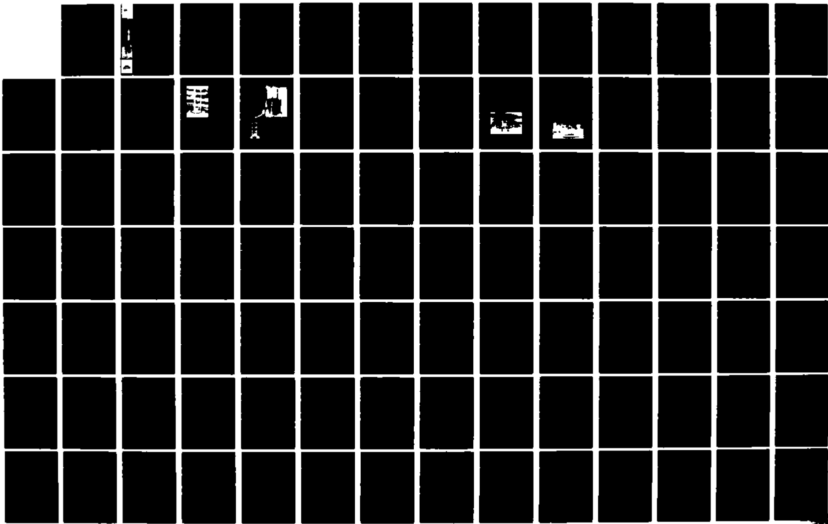

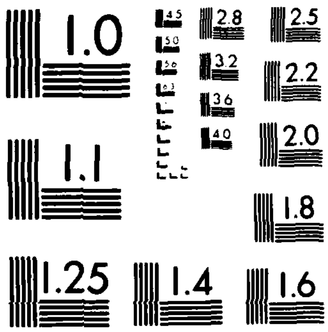
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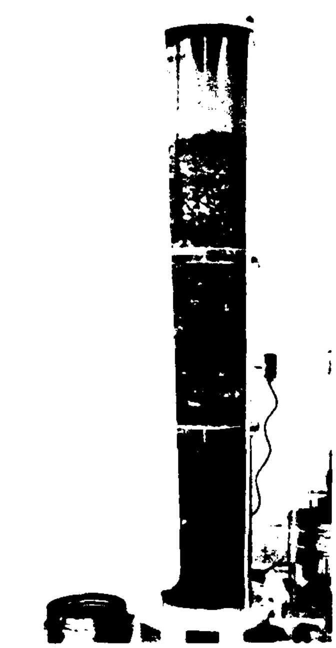

GEOTECHNICAL LABORATORY

TECHNICAL REPORT GL-84-10

INVESTIGATION OF DENSITY VARIATION IN TRIAXIAL TEST SPECIMENS OF COHESIONLESS SOIL SUBJECTED TO CYCLIC AND MONOTONIC LOADING

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The undrained cyclic triaxial test is widely used to evaluate the seismically induced liquefaction potential of saturated cohesionless soil. Concern that internal void ratio changes (redistribution) due to testing characteristics may render the test inappropriate for dynamic analysis prompted research to investigate such changes. This report describes equipment and procedures to:

(Continued)

20. ABSTRACT (Continued).

a. Prepare sand specimens of known average density or void ratio to a high degree of uniformity.

b. Load specimens under undrained (constant volume) conditions to various pore pressure and strain responses.

c. Freeze specimens under test conditions in such manner that the soil skeleton is not disturbed by the freezing process.

d. Dissect frozen specimens to establish spatial density distribution.

e. Conduct control tests involving steps a, c, and d only.

This research required specimens with a higher degree of density uniformity than previously demonstrated. A complex trial-and-error laboratory study was conducted to develop equipment and procedures to construct the high-quality specimens. Additionally, special freezing techniques were required to produce an "undisturbed" frozen specimen. This freezing process and the behavior of the triaxial test specimen during freezing are documented.

Control specimens with 100 percent water saturation (B factor of 0.96 or more) were tested in the triaxial chamber, frozen under back pressure and confining pressure with the top drainage line open and the cold temperature source at the base of the specimen, and then dissected into 96 elements in a cold room. The density of each segment and, consequently, the density distribution of the specimen were determined from the ice content. Homogeneity, that is, relative density uniformity, was quantified in terms of the average relative density determined for the 96 elements. Because of the requirement for precise density determination, errors caused by sublimation and measurement uncertainty were examined and are discussed in this report.

Relative density variation caused by undrained cyclic or monotonic deviatoric loading is documented for initially uniform specimens which were interrupted at various stages of cyclic and monotonic loading, frozen, dissected, and analyzed. Relative density dispersion with increase in strain level is shown at three densities, approximately 40, 60, and 70 percent relative density. The spatial changes in density occurring as a result of cyclic loading are observed and indexed in terms of changes in standard deviation of all dissected elements from the average when compared to control tests described in e above. Density redistribution as a result of cyclic and monotonic loading is irrefutably demonstrated and quantified in test specimens of Banding sand, which is a specific gradation of Ottawa sand.

The study demonstrates clearly that a highly repeatable average density from specimen to specimen is not an indication of a high degree of specimen density uniformity. It was also demonstrated that uniform specimens are stronger and more stable under cyclic loading than nonuniform specimens. It was shown that density redistribution begins at pore pressure responses less than 100 percent, but does not become significant until nearly 100 percent pore pressure response or high peak-to-peak strain levels (greater than 5 percent) are reached.

The work is compared with the work of others who have conducted related studies.

PREFACE

Laboratory investigation of density redistribution in triaxial specimens of sand due to cyclic and monotonic loading was requested and authorized by the Office, Chief of Engineers, US Army, under CWIS Work Unit 31145. This investigation was conducted at the US Army Engineer Waterways Experiment Station (WES) during the period January 1979 to September 1982. The investigation was suggested by Professor Arthur Casagrande who served as a consultant to the project until shortly before his death in September 1981. His inspiration and guidance are gratefully acknowledged.

This investigation is one part of a work unit entitled "Liquefaction of Dams and Foundations During Earthquakes," the overall objective of which is to evaluate and to increase understanding of the response of earth dams to earthquakes. This phase of the study deals with the internal response of triaxial test specimens to laboratory monotonic and cyclic loading conditions.

The laboratory work was performed by Mr. P. A. Gilbert, Soils Research Center (SRC), Soil Mechanics Division (SMD), Geotechnical Laboratory (GL), who wrote this report, under the direct supervision of Mr. G. P. Hale, Chief, SRC, and the general supervision of Mr. C. L. McAnear, Chief, SMD, and Dr. W. F. Marcuson III, Chief, GL. Part VII of this report, "Implications of this Study," was prepared by Drs. P. F. Hadala, Assistant Chief, GL; A. G. Franklin, Chief, Earthquake Engineering and Geophysics Division, GL; and W. F. Marcuson III. The engineering judgments expressed therein are theirs, rather than the author's.

The Commander and Director of WES during the preparation and publication of this report was COL Tilford C. Creel, CE. Mr. Fred R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
British thermal unit (59° F)	1,054.80	joules
cubic feet	0.02831685	cubic metres
cubic inches	16.38706	cubic centimetres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6,894.757	pascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	645.16	square millimetres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

INVESTIGATION OF DENSITY VARIATION IN TRIAXIAL TEST SPECIMENS OF COHESIONLESS SOIL SUBJECTED TO CYCLIC AND MONOTONIC LOADING

PART I: INTRODUCTION

Background

1. Liquefaction is a phenomenon in which a loose, saturated sand stratum suddenly loses so much of its shear strength that it appears to flow like a liquid. The transformation of the sand mass from the solid to the liquid-like phase is accompanied by a considerable increase in pore pressure and a corresponding decrease in strength. The precise definition given by Seed (1979) is "liquefaction denotes a condition where a soil will undergo continued deformation at a constant low residual stress or with low residual resistance, due to the buildup and maintenance of high pore-water pressures, which reduce the effective confining pressure to a very low value; pore pressure buildup leading to liquefaction may be due either to static or cyclic stress applications and the possibility of its occurrence will depend on the void ratio or relative density of a sand and the confining pressure; it may also be caused by a critical hydraulic gradient during an upward flow of water in a sand deposit." The conditions necessary for liquefaction have been discussed by many investigators, including Whitman (1970), Seed and Idriss (1970), and Terzaghi and Peck (1948). The properties of liquefaction-susceptible soils and conditions necessary for liquefaction are summarized and discussed in relative detail by Gilbert (1976), but briefly stated, in order to liquefy, a soil must be loose and water-saturated and possess little cohesion (plasticity index (PI) <20). Additionally, a triggering mechanism must initiate the process. Seismic activity is the most significant triggering mechanism because of the tremendous energy released during an earthquake. Since the liquefaction of embankments or foundation soil supporting embankments can cause rapid and severe damage to civil engineering structures, it is important to identify liquefaction-susceptible materials in seismically active areas so that appropriate defensive measures can be taken. The cyclic triaxial test developed by Seed and Lee (1966) in the mid-1960's is the laboratory test most commonly used to evaluate seismic liquefaction susceptibility of soils.

Casagrande (1936) investigated the stability of sand and developed the concept of critical void ratio. More recently, Casagrande along with Castro (1969) developed laboratory tests to precisely define the critical void ratio as a function of confining pressure and sought to explain liquefaction in terms of this concept. Seed and Lee (1966) contended, however, that the critical void ratio concept is inadequate to explain entirely liquefaction induced by vibratory loading and that this mechanism is more precisely modeled by the undrained cyclic triaxial test.

2. Casagrande (1975) stated that the undrained cyclic triaxial test is inappropriate because the mechanism of cyclic loading causes internal density redistribution within the laboratory specimen. For example, cohesionless soils below the critical void ratio, as defined by Casagrande (1936), tend to dilate upon the application of a shear strain. In the undrained state, such a soil in a static triaxial compression test will develop negative pore-water pressure, which will increase the effective stress and render the soil more stable. However, it has been shown (Seed and Lee 1966) that in the undrained cyclic triaxial test, saturated specimens below the critical void ratio have been observed to develop positive pore pressures of up to 100 percent pore pressure response under intense and continued cyclic loading. In a saturated undrained triaxial test, the volume, and hence the average density, remains unchanged during loading. Casagrande reasoned that, based on his critical void ratio investigation, significant positive pore pressure can only develop in cohesionless soils above the critical void ratio. Therefore, intense and continued cyclic loading in a saturated undrained triaxial test specimen must cause internal density or void ratio changes such that loose and dense zones develop in the initially uniform specimen during cyclic loading (with respect to the initial condition). The loose zones allow positive pore pressure to develop causing the pore pressure measured at the end caps to increase. But because the average density is unchanged, the measured positive pore pressure at the specimen ends and the indicated instability are believed artificial, resulting from laboratory test conditions which induced internal density redistribution. Casagrande stated such redistribution does not occur in situ. Therefore, material properties measured in such a test reflect laboratory conditions that are not representative of in situ material behavior. Consequently, dynamic analyses based on such tests would be erroneous.

3. Because cyclic triaxial test results are widely used for dynamic

analysis and design and usually give a more conservative interpretation of liquefaction potential than does the critical void ratio concept, it is important to evaluate the issues raised by Casagrande.

4. At the fundamental level, this investigation deals with the assumptions basic to any laboratory material property test, namely a homogeneous specimen and a known uniform state of stress or strain (in both spatial and temporal senses). In the cyclic triaxial and the monotonic $\bar{R}$ tests to be considered in this study, the state of stress is assumed to be known and to be uniform. However, the test specimen does not maintain its initial right circular cylindrical shape during deformation and it has long been recognized that the use of end platens that are not frictionless results in nonuniform stress within statically loaded specimens (Shockley and Ahlvin 1960). The effect of this nonuniformity in static ultimate strength determination has been found to be tolerable. Its effect on pore pressure and deformation response during cyclic loading is not so well known. The work of Vernese and Lee (1977) indicated that changing from regular to low friction end caps caused the cyclic strength of sand to increase 10 to 30 percent at a given number of cycles. However, at a given stress ratio, the number of cycles to a given deformation level or pore pressure response increased by a factor from 3 to 5. These data are evidence that changing the end conditions changes the deformation level and pore pressure response of a cyclic triaxial test and suggests that a nonuniform stress state within the specimen is one of the factors responsible for the internal void ratio redistribution that Casagrande believed was taking place.

Objective and Scope

5. The objective of this study is to investigate whether density redistribution occurs in undrained stress-controlled triaxial test sand specimens as a result of cyclic or monotonic loading. Because of the nature of this study, special testing procedures and equipment were required to accomplish this research. A relatively detailed description of the hardware and laboratory procedures as well as the test results will be given.

Description of the Problem

6. In order to investigate the question of density redistribution in a

laboratory test specimen during loading, the state of density uniformity prior to loading must be known and a procedure to explore the density field as a function of position within the triaxial specimen must be developed and employed. These problems were particularly difficult because the soil under study was cohesionless. In addition, the purpose of the investigation was, effectively, to evaluate a laboratory test which required extraordinary care and precision. Density uniformity, a quality normally assumed or inferred in a laboratory specimen, had to be not only achieved but demonstrated. During the course of this study, it was conclusively demonstrated that highly repeatable average density was in no way correlative to a high degree of density uniformity. Specimens of unusual density uniformity were judged necessary to confirm or dispel the question of density redistribution because under some circumstances small density changes were all that were required to move the state of a sand from one side of the critical void ratio line to the other. Professor Arthur Casagrande,* who was directly involved in this study since its inception, recommended the uniformity specification that the triaxial specimens in this study be slightly more uniform than those specimens tested in the study reported by Casagrande and Rendon (1978). Those specimens had a standard deviation typically of 2.66 percent relative density percentage points in a specimen dissected into 64 elements (data points). The recommendation for this study was a standard deviation of 2.0 percent relative density percentage points in a specimen dissected intc 96 elements. Uniformity in terms of standard deviation will be discussed in detail in Part II, but this uniformity requirement was stringent because of the larger size of the triaxial test specimen, the larger number of dissected elements, and a lower required standard deviation than that of the very uniform specimens of the 1978 study. A procedure for reconstituting specimens meeting these specifications had to be developed.

7. In order to examine internal density distribution, it was decided to freeze completely saturated specimens, dissect them into numerous small elements, and determine the density of each element. Casagrande and Rendon (1978) had pioneered this approach to spatial density mapping of sand specimens, and the work of Singh, Seed, and Chan (1979) confirmed that negligible volume change occurred if specimens were frozen under back pressure and confining pressure and offered increased confidence in this approach. Equipment

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* Personal communication, 1979.

and procedures had to be developed to freeze specimens inside a pressurized triaxial chamber without disturbance, to dissect the frozen specimens into small elements, and to handle the small frozen elements so that serious errors did not enter the analysis.

Material

8. The soil used in the study was a clean, fine uniform white quartz sand classified SP in the Unified Soil Classification System known as Banding sand. It is a specific gradation of Ottawa silica sand and is sold by the Ottawa Silica Company, Ottawa, Ill. The average specific gravity is 2.65, the D_{50} size is about 0.2 mm, the coefficient of uniformity is about 1.4, and the grains are subrounded to subangular. One percent by weight is retained on the No. 270 sieve with no material passing. The minus-200 material is nonplastic with essentially the same character as the coarser material. The Ottawa Silica Company advertises a very specific grain-size distribution for the material as shown in Figure 1. The material, as received in 100-lb* bags, was slightly coarser than the advertised gradation, which was also reported to be the grain-size distribution used by Castro (1969) and Casagrande and Rendon (1978). The sand to be used in the present investigation was matched with the advertised gradation by scalping out 99 percent of the plus No. 40 sieve size material. Maximum and minimum density values determined using the procedure outlined in EM 1110-2-1906 (Headquarters, Department of the Army, Office, Chief of Engineers 1970) are 109.1 and 91.5 pcf, respectively.

9. Monterey 0 sand has been used extensively in research investigations on the cyclic and dynamic behavior of cohesionless material. For this reason its grain-size curve is shown in Figure 1 for the purpose of comparison. It is described by Mulilis, Chan, and Seed (1975) and is a washed uniform medium-to-fine beach sand composed of quartz and feldspar particles. The average specific gravity is 2.65 and the coefficient of uniformity is 1.5. The maximum and minimum dry unit weight determinations performed in accordance with the ASTM test for relative density of cohesionless soils are 105.7 and 89.3 pcf, respectively.

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* A table of factors for converting US customary units of measurement to metric (SI) units is presented on page 4.

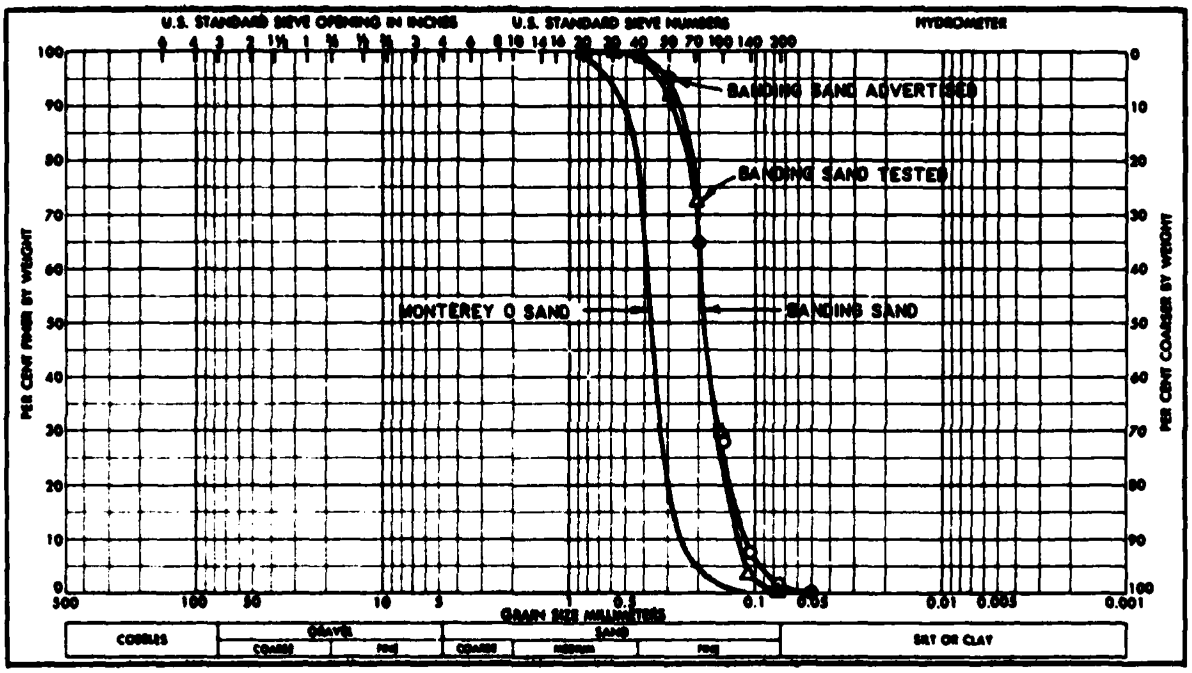

Figure 1. Grain-size distribution of Monterey 0 and Banding sands

PART II: EXPERIMENTAL PROCEDURE

10. The development of an experimental procedure to build test specimens for this investigation was difficult because of the stringent requirement for uniformity in the specimens. Consequently, early in the study, several techniques were explored which did not yield specimens of the required uniformity. These investigations were of interest in that they point out certain conditions and operations which tended to aggravate the introduction of nonuniformity in reconstituted sand specimens. The early experimental pursuits produced data which demonstrated very clearly that a highly repeatable average density in successive specimens is not an indication of a high degree of uniformity. This early work is described in Appendix C. The procedure for reconstitution described below is that used to produce specimens tested in this study.

11. The experimental procedure determined to be the most satisfactory consisted of 11 steps--reconstituting, initial freezing, lathing, placement in triaxial chamber, thawing, saturation, consolidation, cyclic loading, refreezing, dissection, and analysis.

Reconstitution

12. Specimens 4 in. in diameter and 8 in. in length were formed one layer at a time by allowing a premeasured weight of sand to settle through a column of water inside a split acrylic cylinder (Figure 2). A completely saturated system was required; therefore water inside the cylinder was de-aired by applying vibration under a high vacuum to cavitate the water, allowing dissolved and free air to rise up and out of the cylinder. The specimen was formed in 10 layers of equal weight. Sand comprising each layer was weighed and placed along with water in a flask and boiled with heat and vacuum to remove all air. The flask was then filled to the top with de-aired water. To place a sand layer, the mouth of the flask was stoppered, the flask inverted, and its neck placed beneath the level of water in the acrylic mold. When the stopper was removed, sand flowed out of the flask and into the cylinder without coming into contact with air, thus maintaining a high degree of saturation in the system. As the sand poured out, the flask was slowly moved about to produce a nearly uniformly thick layer.

Figure 2. Split acrylic cylinder for molding samples

13. The layers were finally leveled using a rotating blade attached to a rod of adjustable length. The assembly holding the rod was mounted on a frame surrounding the acrylic cylinder. The rod and blade were incrementally lowered with an adjustment screw and rotated until the top surface of the layer was smooth and level (Figure 3).

14. Sand deposited in this manner formed very loose layers, measured to be anywhere from minus 10 percent to zero percent relative density. Specimens deposited in this manner will be called "wet pluviated" below. Compactive energy was then applied to the system to bring the layers to the desired density. Relative densities of approxi mately 40, 60, and 70 percent were tested in this investigation. The procedure to place specimens at 60 percent relative density was developed first and was accomplished by vibrating the frame and acrylic cylinder in which the specimen was formed. The vibration was produced by allowing a 1-lb weight to fall 6 in. and impact against the frame (Figure 4). The traveling waves produced by the disturbance traveled down the rods and up into the specimen through the base as can be seen from Figure 4. Specimens at 70 percent relative density were formed by applying compactive energy with a vibrating table. The procedure is described in paragraph 16 below.

15. Because the energy application was indirect, with the first layer placed "feeling" all the energy applied to the system and the last layer "feeling" only the energy applied after its placement, a prorated schedule of blows was required which would bring all layers to the same density. The procedure was developed by trial and error, proceeding by arbitrarily selecting a

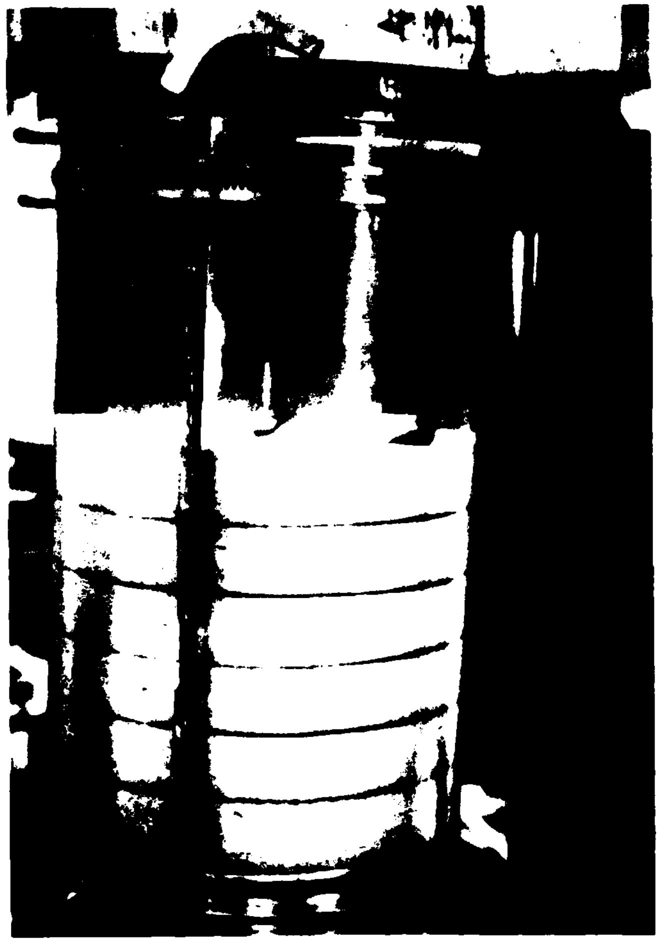

Figure 3. Leveling blade inside molding cylinder

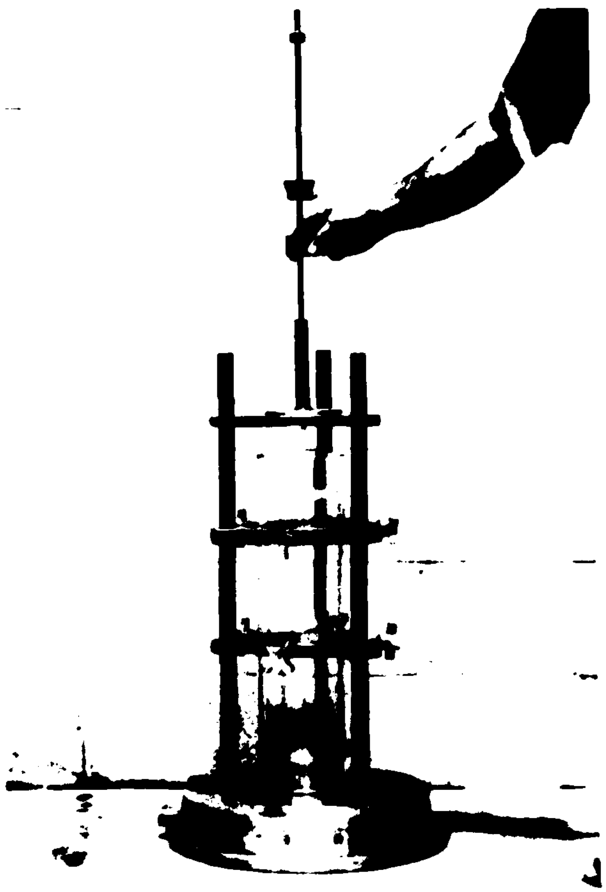

Figure 4. Impact hammer mounted on the frame

schedule of energy application, building a specimen, freezing it, dissecting it, and analyzing it for density uniformity. It was quickly learned that the procedure of lathing 1/2 in. from the outer periphery of the specimen resulted in layers satisfying the uniformity requirement in the radial direction (i.e., in the plane of the layer) so it became necessary only to satisfy the uniformity requirement in the vertical direction. This was accomplished by observing the average density in the various vertical layers and increasing or decreasing the number of blows applied to each layer to bring each layer to an average relative density which did not vary more than ±2.5 percent relative density from any other layer. The final schedule of energy application was a series where the number of blows increased logarithmically from 25 for the first layer (bottom) to 300 for the tenth layer (top) to produce specimens at 60 percent relative density.

16. Specimens at 70 percent relative density were formed by wet pluviation. The triaxial baseplate and frame were fastened to a vibrating table to apply vibratory energy with the table. The table consisted of a three-dimensional frame structure supporting a 30-in.-square, 3/8-in.-thick steel plate which was attached to the frame through 1/4-in.-thick pads of viscoelastic rubber, one on each edge of the plate. A massive electronically driven magnetic vibrator was fastened to the plate through very stiff precompressed springs. Tables of this type are described in American Society for Testing and Materials (ASTM) Specification D 2049 (ASTM 1983). The table operates at a frequency of 60 Hz, which was measured with an accelerometer and the waveform observed with an oscilloscope. The operating frequency of the table was fixed and uncontrollable, but the amplitude of vibration could be adjusted with a rheostat with given rheostat settings corresponding to a given acceleration and hence energy level. The mechanism of energy application on the table was almost identical to that produced by the falling weight, with the energy entering the specimen indirectly from the bottom in both cases. For specimens at 60 percent relative density, the number of blows per layer was the control on the amount of energy applied with the falling weight. Similarly, time exposure per layer and rheostat setting were the controls on the energy applied by the table to achieve 70 percent relative density.

17. The time exposure and rheostat setting to produce specimens at the required density were developed by trial and error. The rheostat setting was held constant and the time exposure per layer was varied logarithmically.

18. To produce specimens at 70 percent relative density, a rheostat setting of 50 was used (which produced an acceleration of about ±0.27 g's) and the time exposure varied logarithmically from 30 sec in the first layer to 3 min in the tenth layer. To produce specimens at 45 percent relative density, the first layer was exposed for 30 sec with a logarithmic variation up to 2 min, 45 sec in the tenth layer. The first five layers were not leveled with the rotating blade because the applied vibration resulted in their liquefaction and self-leveling. It was necessary to use the blade to level the remaining five layers. The rheostat setting for the first five layers was 38 (which produced an acceleration of about ±0.11 g's); for the second five layers, 35 (slightly less than ±0.11 g's).

19. This procedure was learned by trial and error by building a specimen, freezing and dissecting it, noting where mismatches or nonuniformities in the specimen occurred between layers, and modifying the schedule of energy application accordingly in a manner exactly like the trial-and-error procedure described in paragraph 15 above.

20. Since vertical vibration was preferable to transverse vibration which caused acceleration variation over the height of the specimen, it was necessary to clamp the vibratory table at various locations to minimize undesirable transverse vibration. Waveforms in the table were observed with an oscilloscope and an accelerometer to pinpoint positions to clamp the table for optimum performance. It should be stated that the observed waveforms became very erratic with increasing rheostat setting. However, the acceleration level at a given setting was, fortunately, repeatable.

21. It was decided, after completing a series of tests at about 45 percent relative density, that at this relatively loose density, the vibratory table was too erratic to produce repeatable and uniform specimens. Therefore, this series was repeated, building specimens using the same drop hammer technique as were the original specimens at 60 percent relative density with the energy application modified to achieve a lower relative density. With the modified energy schedule, the 1-lb sliding weight fell 4 in. (instead of 6) to impact against the frame and the schedule of blows varied logarithmically from 12 in the first layer to 200 in the tenth layer and produced uniform specimens at about 40 percent relative density.

22. The black bands between the layers as seen in Figure 3 were marker beds placed to identify each layer. Each marker consisted of 5 g of Banding

sand which had been dyed black with India ink. The thickness of the black ink on the individual grains was infinitesimal and is presumed not to have altered the properties of the sand forming the marker beds. This marking system allowed not only the identification and examination of individual layers, but also observation of axial deformation patterns during loading.

23. In the search for a technique to produce specimens of the required uniformity, it was determined, by dissecting specimens into radial segments so that variation in density with radial distance could be investigated, that portions of specimens around the periphery evidently absorbed more energy than the interior and, consequently, became more dense. It was therefore necessary to remove this peripheral material to achieve the specimen uniformity required. To accomplish this, the specimen was constructed oversize, frozen in the mold without confining or back pressure, and turned down on a lathe. The two end layers were also removed from the frozen specimen to improve the homogeneity of the remaining specimen.

Initial Freezing

24. Specimens 4 in. in diameter and about 8 in. high were tested; therefore, oversize specimens 5 in. in diameter and 10 in. high were formed to allow for boundary removal. Specimens were frozen on the triaxial base platen which was designed as the evaporator of a self-contained refrigeration system. The associated condensing unit was a commercially available Copeland low temperature unit driven by a 1/2-hp compressor. The unit used refrigerant R-12 and operated in an ambient temperature of 75° to 80° F. The performance characteristics at this ambient temperature are shown in Figure 5. Condensing unit suction pressure was monitored during freezing and decreased from about 85 psia at initial operation down to 12 psia at steady state which indicates a steady state evaporator temperature of -30° F and a heat removal capacity of 1,500 btu/hr. The evaporator itself is a cylinder 4 in. outside diameter and 5.25 in. high, with an internal volume of 48 in.^{3} A 1/4-in. copper standpipe served as the suction tube inside the evaporator and carried away the hot gas. The triaxial baseplate with the oversize adapter is shown in Figure 6. The adapter is simply an aluminum cap which fits tightly over the pedestal to ensure good heat transfer and which allows the forming of an oversize specimen.

25. After specimens were formed, a surcharge of about 1 psi was applied

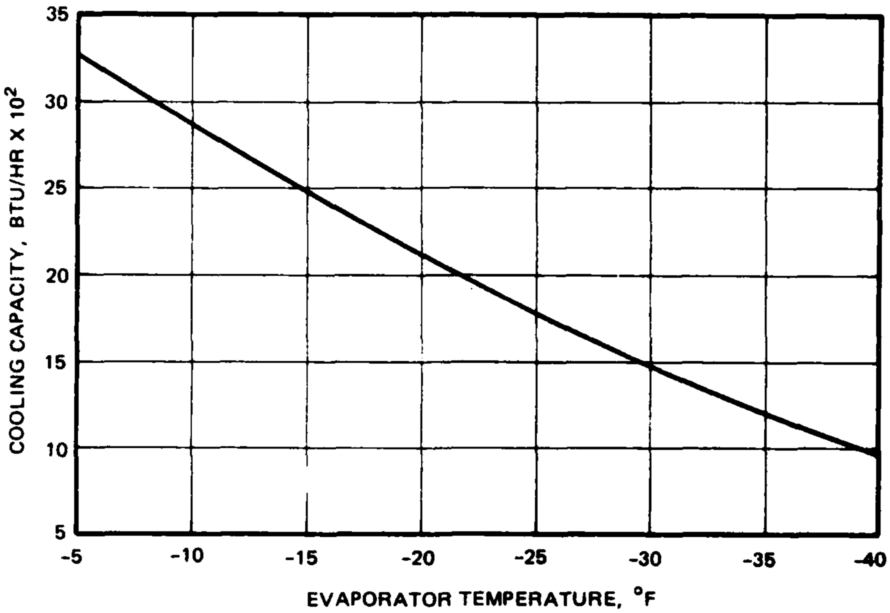

Figure 5. Cooling capacity of condensing unit in 75° F ambient temperature

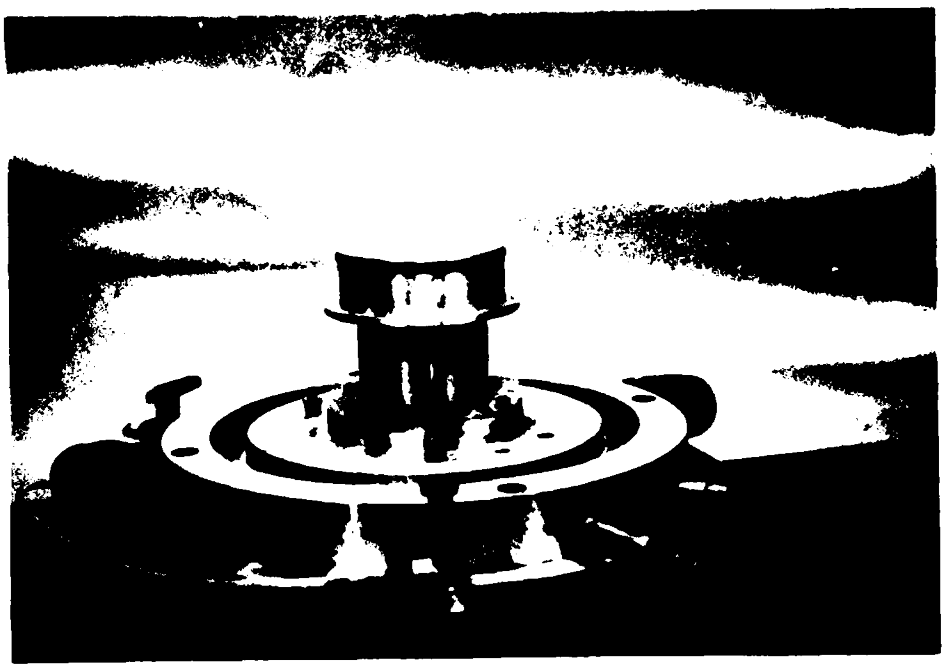

Figure 6. Triaxial baseplate showing oversize adapter

to the top of the specimen through a perforated metal plate to maintain grain-to-grain contact during freezing. A split copper tube was clamped around the acrylic mold to transfer heat to the base platen. The entire system was insulated by covering it with Styrofoam bits. The specimen required 12 to 16 hr to freeze, depending on the ambient temperature of the laboratory.

Lathing

26. After freezing, the specimen was removed from the triaxial base and allowed to come to thermal equilibrium in an environmental room maintained at 20° F. Each end of the specimen was then set into a cylindrical metal cap and the space between the specimen and cap was filled with ice water. When this water froze, the specimen and caps became a rigid unit which was chucked in a small metal cutting lathe with the chuck jaws clamping on the metal caps. Without the protective caps, the jaws would have cracked the brittle frozen specimen. The diameter was trimmed down using a carbide-tipped cutting tool and a spindle speed of 540 rpm. The specimen is shown mounted in the lathe in Figure 7. One inch was removed from the specimen diameter, with 0.100 in. of diameter taken off by each of 10 passes. The ends were then sawed with a band saw and squared by hand with a metal straightedge and a metal miter box. The resulting frozen specimen was 4 in. in diameter and about 8 in. high.

Figure 7. Frozen specimen mounted in lathe

27. Special steps were required for using the lathe and band saw inside the environmental room. The thick lubricant on the bearings had to be removed and replaced with a light oil and the 30-weight oil in the gear boxes had to be replaced with 10-weight oil in order to operate satisfactorily in the low temperatures inside the room. Sand particles comprising the specimens were very hard and abrasive. Cutting tools were worn down to the point of uselessness after machining two specimens. Two band saw blades were required for the dissection of one specimen. The procedure of dissection is described in paragraph 47.

Placement in Triaxial Chamber

28. After lathing, the specimen was weighed, measured with calipers measuring to the nearest 0.001 in. to determine the diameter and height, and carried to the triaxial cell inside a Styrofoam container. The refrigeration system had been running for about 1 hr so that the pedestal and base were very cold. The triaxial specimen top cap had been prechilled in the 20° F environmental room. The specimen was set on the pedestal, the cap placed on it, the membrane positioned with a stretcher and secured with O-rings around the cap and base, and the top drainage lines connected to the specimen top platen. The acrylic pressure chamber and top platen were then put in place and the external drainage and control lines attached. A vacuum was applied to the specimen and the chamber filled with a 60 percent solution of ethylene glycol which had been prechilled to 20° F. The arrangement is shown schematically in Figure 8.

Thawing

29. The triaxial chamber was then mounted in its loading frame and the refrigeration system shut down to allow the specimen to thaw. During thawing, a vacuum of about 28 in. of mercury was applied to the porous stone in the top cap through a burette containing a small amount of water. This procedure prevented the intake of air and the consequent loss of saturation. The thawing process required about 20 hr during which time specimen height was monitored with a dial gage. The maximum decrease in height during thawing was 0.010 in.

30. Thermocouples at various levels inside the chamber indicated that the temperature increased from the top downward with time, due to the large

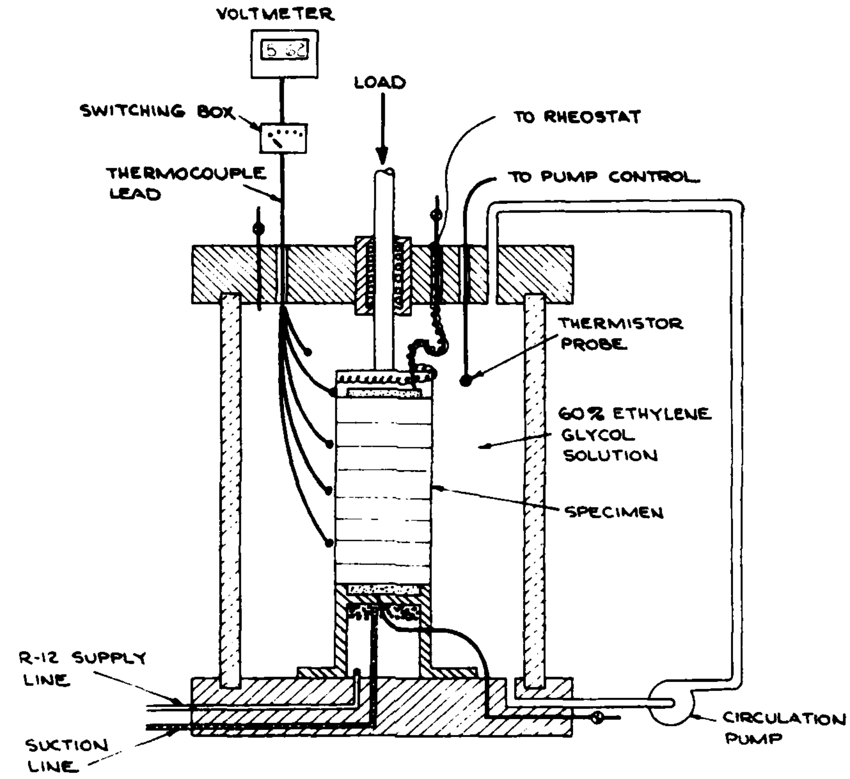

Figure 8. Schematic of triaxial equipment

mass of cold aluminum at the base, the insulation provided by the acrylic chamber cylinder, and the aluminum top plate at room temperature. This was very desirable since it undoubtedly permitted nearly uniaxial thawing in the specimen from the top downward.

Saturation

31. With the high vacuum still applied to the soil pore space, the burette connected to the porous stone at the bottom of the specimen was filled with de-aired water. A differential of 1 in. of mercury was established from the specimen top to bottom and about 300 cm^3 of highly de-aired water was allowed to seep through the specimen under this gradient. Any air which had been trapped in the plumbing system was flushed out during this operation.

32. Back pressure was then applied by increasing the pressure inside the specimen and in the triaxial chamber simultaneously while maintaining an effective pressure of 15 psi on the specimen. This operation decreased the volume of any free air present in the system and increased the degree of

saturation. Typically, 45 psi of back pressure was applied. Saturation was measured in terms of Skempton's B parameter. The minimum acceptable value was 0.96, but frequently values of 0.98 or greater were measured.

33. A very high degree of saturation was critical to this study, not only in obtaining correct pore-water pressure measurement during cyclic and monotonic loading, but also in precisely determining the density distribution, as will be discussed below.

Consolidation

34. During this phase, the effective confining stress was increased to the level under which the specimen would be loaded while access to drainage was allowed. Specimens were (with one exception) consolidated under a hydrostatic effective stress of 15 psi for this program. Volume and height changes were monitored and occurred almost instantaneously for the free-draining sand tested.

Loading

35. Cyclic loading consisted of applying a sinusoidally varying deviator stress to the specimen at a frequency of 1 Hz beginning from a condition of hydrostatic compression. The specimen was undrained during this process and pore-water pressure, chamber pressure, and axial deformation were monitored. Loading was continued until a predetermined level of either pore-water pressure or deformation had been reached at which time the loading was interrupted and manually set to the maximum compressive value in the last cycle. This procedure could not, of course, be used in loose specimens (of 40 percent relative density) which had reached 100 percent pore-pressure response or such a high pore-pressure response that the specimen could not support the full axial load without deforming excessively. These cases were handled by either applying a small (1- to 5-lb) axial load in excess of the chamber pressure uplift load, or locking the load piston in place during refreezing.

36. The equipment used for cyclic loading was a commercially available pneumatic sine-wave loader built by Soil Engineering Equipment of Richmond, Calif.; the triaxial cell was designed and fabricated at the US Army Engineer Waterways Experiment Station (WES). The specimen cap and base were of the

same diameter as the specimen and contained porous bronze inserts which had essentially the same area as the specimen. (The diameter of the specimen was 4 in. and the diameter of the insert 3.8 in.; therefore, the area of the insert was 90 percent of the area of the specimen.) Load was measured with a miniature (Transducer, Inc.) electronic load cell of ±500-lb capacity mounted on the piston below the pneumatic actuator outside the pressure chamber. The load piston was sealed by a rubber O-ring as it entered the pressure chamber and about 1/2-lb O-ring friction was measured as the piston was forced slowly through the seal. The chamber pressure was measured with a Baldwin-Lima-Hamilton (BLH) 200-psi-capacity pressure transducer and the pore-water pressure was measured with a 250-psi-capacity Bell and Howell pressure transducer utilized for pore-pressure measurement because of its low volume change characteristics (5×10^{-5} in.^{3}, full scale). To ensure an adequate air supply for the sine-wave loader during extended cyclic tests, a 30-ft^3 tank adjacent to the loader was employed and maintained at 200 psi. To ensure adequate airflow, 1/2-in. air hoses were used.

37. Monotonic loading consisted of applying axial compressive load increments with a pneumatic actuator, beginning from a condition of hydrostatic compression. Load increments were applied about 45 sec apart by increasing pressure to the actuator with a regulator. The time required to increase the pressure was about 5 sec. Monotonic loading was continued until a predetermined strain/deformation level had been reached. During monotonic loading, pore-water pressure, chamber pressure, and axial deformation were monitored while the lateral pressure was held constant and no drainage allowed.

Refreezing

38. After loading, pressure in the burette connected to the top drainage line was carefully matched with the specimen pore-water pressure measured at the top cap and the drainage valve opened. This operation was done carefully so that no volume change occurred. Electrical resistance heating tape, which was wrapped around the top drainage line to prevent it from freezing, was turned on. It was necessary to use a small pump to periodically remove cold fluid from the bottom of the chamber and circulate it through the top of the chamber in order to maintain the desired temperature in the chamber fluid (Figure 8). The operation of this circulation pump was controlled automatically

by a temperature sensor which measured the fluid temperature near the top of the specimen. If the fluid temperature there was greater than 32.5° F, the temperature sensor activated the pump through a relay circuit, mixing in cold chamber fluid. When the fluid temperature became slightly less than 32.5° F, the pump was turned off. At the beginning of the refreezing operation, the refrigeration system and the circulation system were activated. The circulation pump ran continuously until the fluid temperature was lowered to just below 32.5° F. At this time the pump shut off and then operated intermittently until the specimen was frozen. The refrigeration system ran continuously during the operation.

39. The chamber fluid circulation effected by the pump maintained the chamber fluid temperature around the specimen just above the freezing point of water and consequently heat carried out through the refrigerated base was sufficient to allow the specimen to freeze. This operation also ensured that the freezing front in the specimen remained approximately horizontal as it proceeded upward avoiding entrapping pockets of water which would eventually freeze and expand to disturb the specimen structure. Since water expands about 9 percent as it freezes, the excess volume was expelled into a burette maintained at a constant pressure equal to the pore-water pressure at the interruption of loading. Specimen height change was monitored during freezin, and found to be always less than 0.025 in. The refreezing process produced a frozen specimen where the grain-to-grain skeleton was essentially unaltered by the freezing. The volume of water expelled was carefully monitored, and a typical time-versus-volume plot is shown in Figure 9. This plot shows that freezing proceeds rapidly initially, but slows down as the process continues. Freezing is complete when the time-volume relationship becomes horizontal; i.e., when no further water expulsion occurs. At this point the triaxial equipment was disassembled, and the specimen was removed, wrapped tightly in aluminum foil, and allowed to come to thermal equilibrium in the 20° F environmental room for 16 to 24 hr. To investigate the time required for complete equilibrium, a specimen of sand and ice with a thermocouple probe at its geometric center was cooled to -18° F and put in the 20° F environment. Temperature rise with time was observed and is shown in Figure 10. Equilibrium was reached in 5 hr. Even if the specimen temperature had been -40° F, it is estimated, based on the thermal conductivity of the sand-ice mixture, that equilibrium would have taken no more than 8 hr.

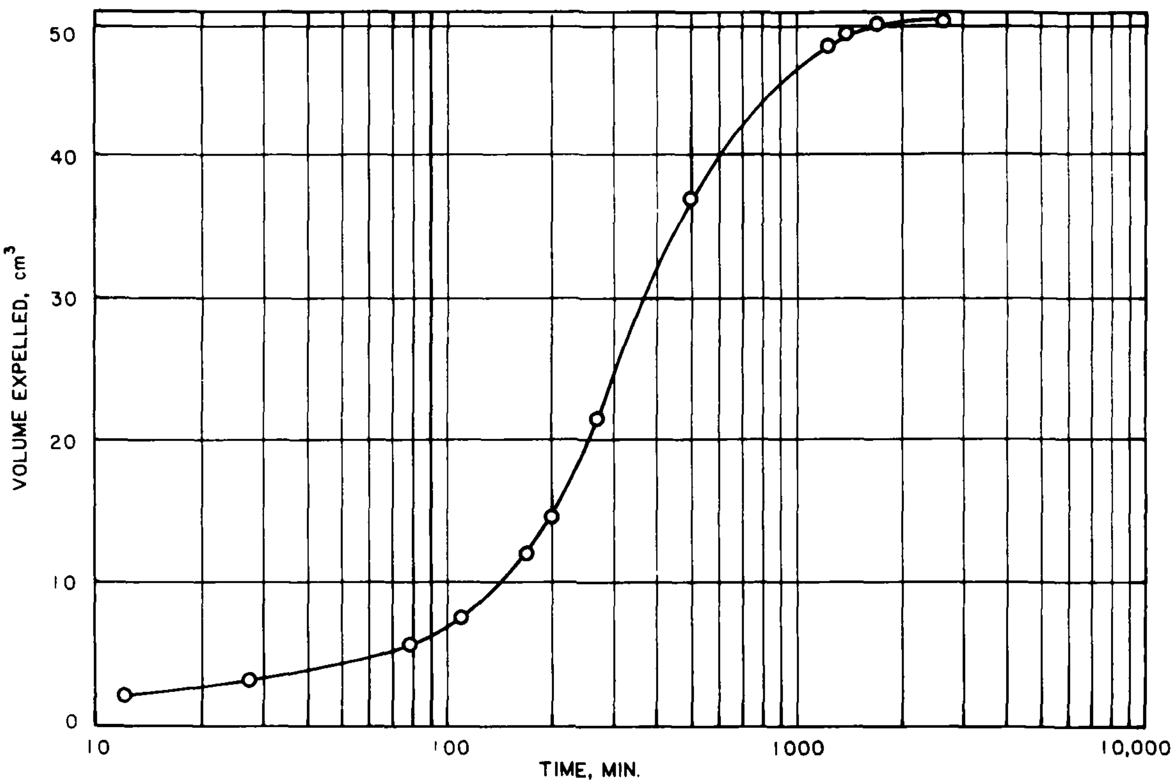

Figure 9. Water expelled versus time during specimen freezing

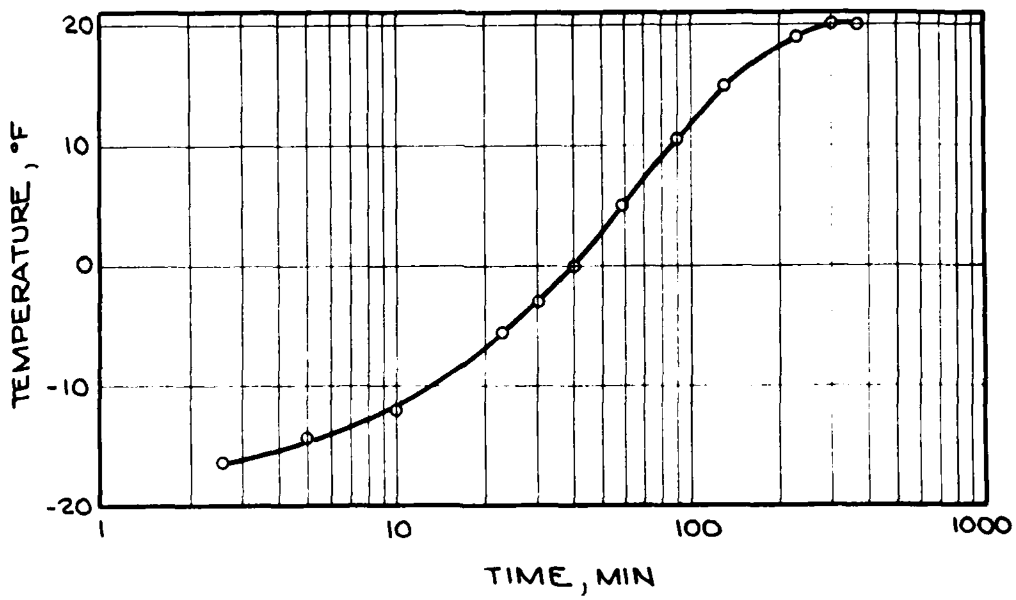

Figure 10. Temperature decay versus time

40. The cyclic loading phase of the test was videotaped so that specimen deformation during loading could be observed; consequently, a transparent acrylic pressure chamber was used. Thermal expansion of the acrylic material was about seven times larger than that of the steel tie rods holding the end plates against the chamber. Under these conditions, as the chamber cooled, the acrylic material shortened so much that it lost contact with the end plates, resulting in chamber fluid and pressure loss. This problem was solved by putting very stiff die springs on the tie rods and compressing them against the top plate with jam nuts. With this configuration, as the chamber shortened, the elastic springs deformed to maintain enough force between chamber and end plates to avoid leaks.

41. At the ice/water interface in water saturated with air, air is rejected during freezing (Michel 1978); that is, air comes out of solution leaving continuous strings of bubbles in the ice. This phenomenon could have presented problems for this investigation since the internal density distribution of the specimen would be determined from the ice content with calculations based on 100 percent ice "saturation." This potentially serious problem was avoided by subjecting the specimen to a high vacuum for 24 to 30 hr before introducing almost completely de-aired water. The air content of the water used to saturate the specimen was measured to be between 0.2 to 0.4 parts per million (ppm) entering the specimen and 0.4 to 0.6 ppm leaving at the end of the flushing operation previously described. Therefore, very little air was available in the specimen to come out of solution during freezing. Water saturated with air freezes as a cloudy opaque mass; whereas, water free from air freezes as a clear transparent mass. In order to investigate the notion of air rejection, a specimen of pure de-aired water contained in a thin acrylic cylinder was set up inside the triaxial chamber and frozen under back pressure in the same manner as the sand specimens. During freezing, water was expelled as the water changed phase. At the freezing interface, small crystals approximately 1/16 in. in height could be observed projecting up from the solidifying surface into the unfrozen water. These structures appeared sheetlike; they were planar and light-reflecting from an obtuse angle view, but so thin that they could not be seen parallel to their plane. These crystals left tiny, spiraling, light-reflecting "tails" in their wake as they moved up with the proceeding freezing surface. However, no air was rejected at the front and the resulting cylinder of ice was clear and transparent with the twisting paths left

by the moving crystals clearly visible. Unfortunately, these delicate details cannot be plainly seen in photographs.

42. The density of the resulting ice specimen which had a volume of about 90 $in.^3$ was determined from careful measurements to be 0.91767 g/cm^3 at -6° C. This compares favorably with a value measured by Boder (1964) who determined the density of ice at -6° C to be 0.91736 g/cm^3.

43. Another advantage of this experiment was that it allowed direct observation of the freezing front and confirmed that the freezing procedure advanced the front approximately horizontally without entrapping unfrozen water. Initially, the advancing surface was inclined at about 15 deg to the horizontal because the chamber fluid circulation system circulates fluid which is initially warm into one side of the chamber. Obviously this warm fluid retards freezing on that side and the freezing surface becomes inclined with the low side under the circulation discharge port. As the chamber fluid cools and approaches the freezing point of water, the surface advances, becoming approximately level as the specimen is half frozen, after which a slight amount of radial freezing occurs and the freezing surface becomes concave upwards. The last zone to freeze in the specimen is a small cylinder at the top in the center which gradually becomes smaller, with a point in the exact center of the cap being the last to freeze. It should be mentioned that initially the chamber fluid was circulated around the specimen manually, that is, an attendant sat and watched the temperature near the top cap and turned the circulation pump on by hand as necessary. When the temperature at the control point dropped to the desired level, the pump was shut off. Manual control proved very unsatisfactory since there was control only when an attendant was available to sit with the apparatus. Often during the early morning hours, the apparatus was left unattended. Heat entered the system through the top cap and the chamber fluid and caused thawing to occur in the upper part of the specimen and freezing time was lost. Because of intermittent manual temperature control and the resulting lost time due to undesired thawing, a period of almost 4 days was required to freeze a specimen.

44. It was decided to automate this operation with an electronic voltage comparative circuit driven by a thermistor, which is a solid-state component that outputs a voltage proportional to its surrounding temperature. The voltage comparator, thermistor, and circulation pump were arranged in a closed-loop circuit which maintained the chamber fluid temperature between two limits.

This system held the chamber fluid temperature continuously between two closely spaced limits and cut the freezing time to about 2,000 min. This improvement, more than perhaps any other, rendered this study practical and reasonable since it cut the total time for a test in half and automated the freezing process so that human influence was completely removed.

45. It should be noted that care was taken to minimize air diffusion into the specimen through the membrane during freezing. Because it was important to maintain complete saturation in the specimen and the freezing process required about 2,000 min during which time air diffusion could occur, special steps had to be taken to minimize the process. First, the chamber fluid was always stored under a high vacuum to prevent it from becoming saturated with air. When the chamber was filled, care was taken to flush all air bubbles from the top of the chamber. An "air cushion" was required inside the chamber to prevent pressure surges during cyclic loading. This was accomplished by inflating a rubber balloon with air inside the chamber space just before cyclic loading and deflating it upon completion of loading. This operation provided the required cushion and yet prevented air from coming into contact with the chamber fluid.

46. Because the rate of gas diffusion through a liquid is proportional to the area normal to the path of movement and inversely proportional to the length of the path, a small-diameter, long tube was filled with de-aired fluid and used between the air-liquid interface and the chamber. The 50-ft-long 1/4-in.-diam tube did not stop the air diffusion, but rather slowed down the process sufficiently that specimen saturation was not affected during the freezing process.

Dissection

47. During dissection, frozen specimens were cut into 96 elements of about 1 in.^{3} each with a band saw inside the environmental room. The location of each element was carefully cataloged so that the density distribution of the specimen would be known when the density of each element was determined. The specimen was first cut into eight discs of about equal thickness; then each disc was cut into 12 elements in the pattern shown in Figure 11. The elements were scraped clean of saw blade smear and placed in capped aluminum tare cans as soon as possible after cutting. This was to minimize ice content

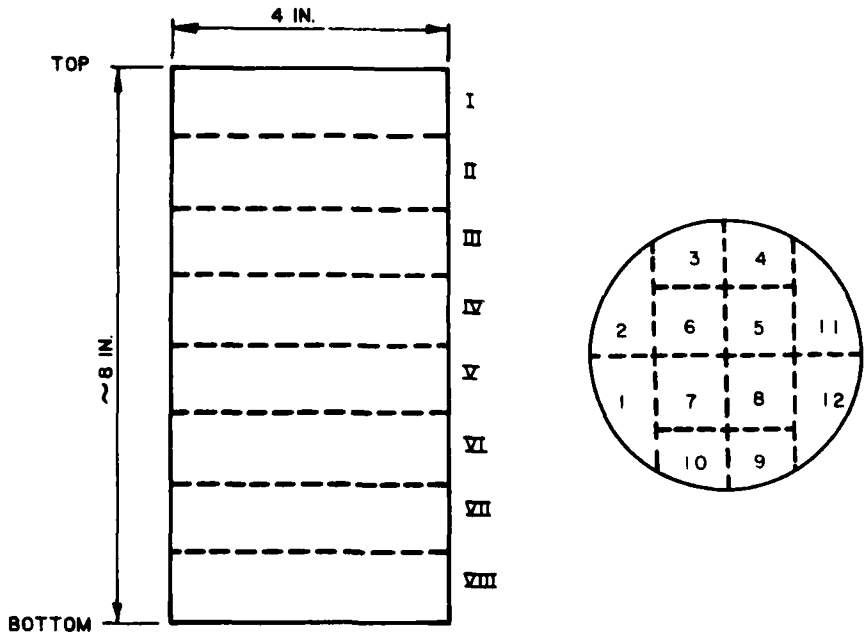

Figure 11. Specimen dissection pattern

loss due to sublimation which occurs when uncovered elements are exposed to the cold environment. The maximum time that an unprotected element was exposed was about 2 min. A sublimation study on specimens of different mixtures and geometries established the loss rate in the environmental room and is summarized in Figure 12. This shows that the loss for a 2-min exposure is negligible. It was also determined that once a specimen was capped in a tare can or wrapped in metal foil, no further weight loss due to sublimation could be observed.

48. The 96 elements were weighed on an analytical balance inside the environmental room in order to determine the ice content of each element. Weights could be estimated to the nearest milligram. The same scale was then taken out of the environmental room and warmed up to the ambient temperature in air dried with a refrigerant-type air drier to avoid condensation and used to weigh the dissected elements after they had been dried for 24 hr in an oven maintained at 110 ± 5° C. A systematic study was also performed to show that no significant error resulted from moving the analytical balance into and out of the environmental room. The scale was calibrated with precision weights before weighing the dissected elements of a specimen. Careful attention was given to accurate ice content determination because density was obtained using the relationship:

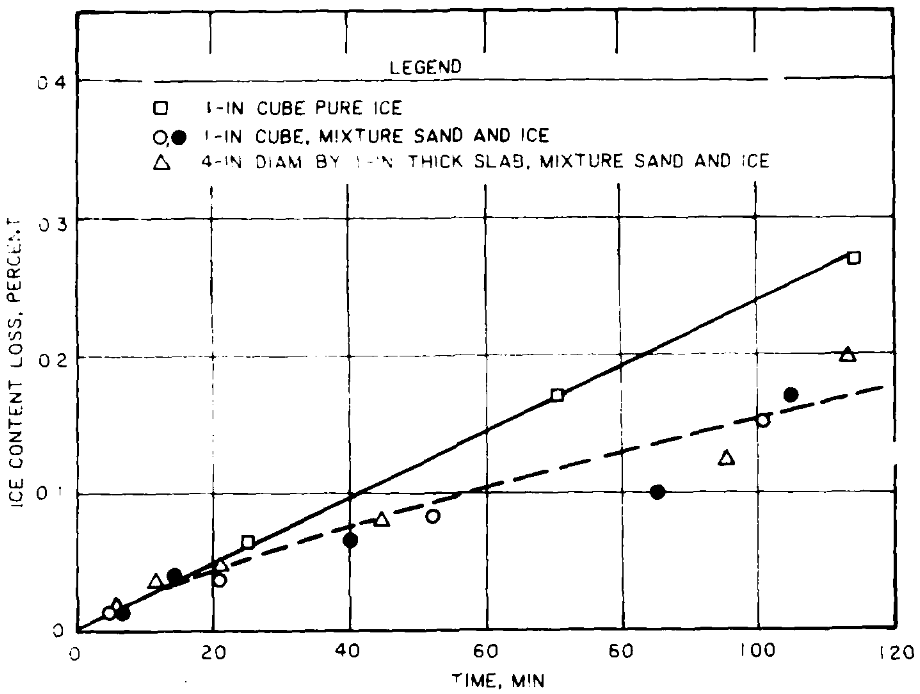

Figure 12. Sublimation versus time study

$$e = G_s w/S \qquad (1)$$

where

e = void ratio of the element

G_s = specific gravity of the solids

w = water content of the element, percent

S = saturation, percent, taken to be 100 percent since B factor ≥ 0.96

Careful measurements were made of the density of a specimen of ice frozen on the triaxial equipment. This allowed determination of the appropriate correction to change ice content into water content since the ice content of elements would be determined. With the correction factor, Equation 1 becomes:

$$e = 1.08936 w_i G_s \qquad (2)$$

where w_i is the measured ice content of the element, expressed as a decimal. From the void ratio, e, accurately determined from ice content, density in any terms could be computed. It was decided to use density as percent relative density for this study. It should be mentioned that the dissection operation and the initial weighing of the tares as well as the lathing of the specimens were carried out in the environmental room maintained at 20° F. Approximately 6 hr were required for these combined operations. Special gloves, clothing, and boots were required to protect the investigator in this environment. The comfort of the investigator was important since not only was it required to make many precise observations, but it was also necessary to work with potentially dangerous machinery.

Analysis

49. Analysis consisted of determining the ice content of each of the 96 elements, converting to relative density, and expressing density uniformity in terms of an index such as the standard deviation from the average of all the elements. Standard deviation was chosen as the appropriate index because it measures the variation or dispersion of a population about an average. Density redistribution by its very nature is intrinsically tied to an increase or decrease in material density variation caused by loading. Specimens were loaded in a constant volume state so the average density must remain unchanged during loading. If redistribution occurs, certain zones within the specimen will become looser, forcing others to become denser. Standard deviation will readily identify such forced dispersion.

50. A computer code was written to accept as input the frozen and dry element weights from which the relative density of each element was computed. The density pattern within each specimen was computed and printed out in a systematic array, and the standard deviations of the elements of the specimen were computed and printed. Elements of various discs and columns were grouped to assist in the identification of density patterns. Specimens which were loaded, as well as control specimens built to determine initial uniformity, were analyzed in this manner and the data inspected for patterns and gradients.

Numerical Evaluation

51. Numerical calculations were quite simple for this investigation, consisting mostly of the determination of water (ice) contents. However, it was convenient to use the computer since 96 ice contents were generally

involved and the standard deviation and other statistical moments were required as well as an operation to write a systematic array such that the results could be visually inspected for patterns.

52. The computer code written in FORTRAN IV for the investigation is shown in Appendix A. It was run on a Honeywell GE 635 computer in the time-sharing mode. A single set of tares was used for ice content determination throughout the study. The tares were numbered and their weights were carefully determined and stored by number as an array in the computer. When the numbered frozen and dry weights were read in as a second array, the program operated on these two systematic arrays to create a third array, which was the water content of the numbered elements, each element tied to a specific location within the specimen.

53. The standard deviation of the elements about the average, which is a measure of dispersion or distribution, was determined. Standard deviation in relative density, σ , was computed from the expression:

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{\left(D_{r_i} - \bar{D}_r\right)^2}{n}} \qquad (3)$$

where

n = number of elements (usually 96)

D_{r_i} = relative density of each element, percent

$\bar{D}_r$ = average value of the relative densities, percent

54. Other statistical parameters computed by the code were the moments of skewness and kurtosis. Skewness is the degree of asymmetry of a distribution. If the frequency curve of a distribution has a longer "tail" to the right of the central maximum than to the left, the distribution is said to be skewed to the right. If the opposite is true, the distribution is skewed to the left. The skewness is computed from the expression:

$$s_1 = \frac{\sum_{i=1}^{n} \left(D_{r_i} - \bar{D}_r\right)^3}{\frac{n}{\sigma^3}} \qquad (4)$$

For perfectly symmetrical curves, the skewness, S_1, is equal to zero. A negative value of skewness indicates a tail to the left and conversely a positive skewness, a tail to the right. Kurtosis is the degree of peakedness of a distribution taken relative to a normal (Gaussian) distribution. Kurtosis was computed from the expression:

$$S_2 = \frac{\sum_{i=1}^{n} \left(D_{r_i} - \bar{D}_r \right)^4}{\frac{n}{\sigma^4}} \tag{5}$$

The kurtosis, S_2, of a normal distribution which is not considered flat or peaked is equal to 3 and is called mesokurtic. The kurtosis of a peaked distribution is greater than 3 and is called leptokurtic. The kurtosis of a flat distribution is less than 3 and is called platykurtic. It should be noted that skewness and kurtosis are defined here as dimensionless numbers. Comparison of the skewness parameter between control and loaded specimens should assist in identifying large loose or dense zones in a specimen which develop as a result of loading. A sharp change in the kurtosis parameter in the loaded specimen may help to quantify redistribution which results in an overall symmetric dispersion of the elements.

55. The code was written to compute and print the standard deviation within each slab as well as the overall standard deviation and was written to handle a variable number of slabs and elements within each slab. The code also warns the investigator of an incorrect or inconsistent number of entries read into the data files.

56. A typical printout of results is shown in Figure B1. The location of the columns (1-12) in Figure B1 is shown in Figure 11. The slabs (I-VIII) are shown there also. The "average percent water content of the entire specimen after test" shown is calculated by summing the weights of all the ice i: the dissected elements and all of the soil particles, taking the ratio of these quantities to get average ice content, and converting to a water content with the correction factor of Equation 2. The "average percent relative density of the entire specimen after test" is calculated by assuming 100 percent ice saturation, converting the average ice content to a void ratio using Equation 2, and finally converting the average void ratio to an average percent relative density.

PART III: TEST PLAN AND PRESENTATION OF RESULTS

Test Plan

57. The objective of this investigation is to determine whether density redistribution occurs in undrained laboratory triaxial test specimens of sand as a result of cyclic and monotonic loading. In order to know whether density redistribution occurs, it is necessary to know the degree of density uniformity just prior to the initiation of cyclic or monotonic loading (that is, at the end of consolidation). In this way, when the degree of density uniformity is determined after loading, any change from the initial state will be attributed to the effects of loading.

58. The determination of density distribution involves a destructive procedure; that is, a specimen must be dissected and effectively destroyed to catalog its density distribution. Therefore, the initial density uniformity condition must be established by testing control specimens--specimens which have been subjected to all the operations of the test procedure except cyclic or monotonic loading. Also, because it is desired to establish whether density redistribution begins to occur at pore-pressure responses less than 100 percent, it was necessary in this study to arrest loading at various levels of pore-pressure response as well as axial strain and examine the degree of nonuniformity at those conditions.

59. It was decided that two control tests would be performed for each relative density investigated if the two agreed within 1/2 percent standard deviation. If the two controls did not agree, then additional controls would be performed and the need to modify the placement technique would be considered in an effort to produce a technique which would consistently produce specimens of the same initial uniformity.

60. Specimens would be tested cyclically to various levels of pore-pressure response and strain to test the hypothesis that redistribution increases as response increases. Monotonic specimens would be tested to various levels of axial strain since it was determined that at these relatively high densities specimens would dilate under monotonic axial load. In monotonically loaded specimens, the hypothesis that redistribution increases as strain level increases (and pore-water pressure decreases) would be tested.

61. It was deemed necessary to investigate whether the compaction

procedure used produced overconsolidation in the test specimens. This was accomplished by cyclically loading two identically placed specimens at 60 percent relative density with the same cyclic stress ratio. One specimen was consolidated to 15 psi and the other to 60 psi; 60 psi was judged to be a high enough effective consolidation pressure that any effect of overconsolidation introduced by the placement technique was removed.*

62. It was also decided to investigate whether redistribution occurs in specimens prepared by more conventional techniques. This was done by testing specimens prepared by the conventional technique of moist tamping. Using this technique, the sand was mixed with 5 percent distilled water. For this study, specimens 9 in. high were prepared using 1-in.-thick layers and a compaction foot with an area one-sixth the area of the specimen. An undercompaction procedure similar to that described by Mulilis, Chan, and Seed (1975) was used and involved a technique where the weight of material for each layer increased such that the relative density of each successive layer increased by 1 percent with the desired average relative density being placed in the middle of the specimen. For example, 60 percent relative density was the target average density in specimens for this study. The first layer was placed at a relative density of 56 percent, the fifth layer at 60 percent, and the ninth layer at 64 percent relative density. After establishing the uniformity in control specimens, a series of specimens was tested to establish whether density redistribution occurs in such specimens.

63. Finally, the response of specimens with controlled nonuniformity was investigated. In this investigation, a specimen was built which was prepared by pluviation through water and was uniform except that one layer near the center of this specimen would be removed and replaced with a layer of a substantially lower density. This was possible because once frozen, the sand specimens could be machined and dissected without any disturbance whatsoever to the soil skeleton. The resulting composite specimen would be placed in the testing chamber, allowed to thaw, subjected to the same testing as the other specimens, and then analyzed for density redistribution.

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* Personal communication, S. J. Johnson, Special Assistant to Chief, Soils and Pavements Laboratory (now Geotechnical Laboratory), US Army Engineer Waterways Experiment Station, Vicksburg, Miss., 4 June 1981.

Presentation of Results

64. The results of all control tests and load tests are summarized in Table 1. Seventy tests were performed. Those tests not presented in the table were test specimens used to develop procedures for placing uniform specimens, except for specimen 48, which was lost due to a power failure, and specimen 65, which was lost due to a membrane leak. When it was believed that a satisfactory procedure of specimen placement had been achieved, the uniformity of the wet pluviated specimen in question was confirmed by dissecting the specimen after freezing it in the mold under no confining pressure, lathing off the periphery, and removing the ends (called "Control F" in the table). If the uniformity of the Control F specimen was found to be acceptable, then control freeze-thaw-freeze ("Control FTF" in the table) tests were performed where specimens were subjected to all operations of the testing procedure except cyclic or monotonic loading. Figures 13 through 17 are plots of cyclic stress ratio versus the number of cycles to various levels of response. Cyclic stress ratio is defined to be the ratio $\pm\sigma_{dc}/2\bar{\sigma}_c$ where $\pm\sigma_{dc}$ = cyclic deviator stress in psi and $\bar{\sigma}_c$ = initial effective confining pressure in psi. Figures 18, 19, and 20 are plots of one-half the deviator stress (defined as $\bar{q}$ below) and pore pressure versus axial strain for the monotonic tests performed. Figures 21, 22, and 23 are plots of the effective stress path in $\bar{q}$, $\bar{p}$ space where

$$\bar{q} = \left(\bar{\sigma}_1 - \bar{\sigma}_3\right)/2 \tag{6}$$

$$\bar{p} = \left(\bar{\sigma}_1 + \bar{\sigma}_3\right)/2 \tag{7}$$

65. Tables 2 and 3 list values and responses for Tests 11 and 18, respectively, which were molded to the same relative density and loaded with approximately the same stress ratio but consolidated to different effective confining pressures. This comparison was made to evaluate concern* that the

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* Personal communication, S. J. Johnson, Special Assistant to Chief, Soils and Pavements Laboratory (now Geotechnical Laboratory), US Army Engineer Waterways Experiment Station, Vicksburg, Miss., 4 June 1981.

Table 1

Summary of Test Results

Test No.	Purpose	Void Ratio After Test e_f	Average Relative Density After Test percent	Stress Ratio $\sigma_{dp}/2\bar{\sigma}_c$	"B" Factor	ΔH During Freezing in.	Number Cycles N	$\sigma_{3f}/\bar{\sigma}_c$ percent	Peak-to-Peak Strain, ε_f percent	Standard Deviation After Test Percent Relative Density	Δ Pore Pressure $u_f - u_c$ psi	Skewness	Kurtosis
					Nominal 60 Percent Relative Density Tests - Wet Pluviation/Indirect Impact Compaction								
10	Control F	0.6384	58.04	--	--	--	--	--	--	1.67	--	0.07	2.40
11	75% PWP	0.6434	56.36	0.21	0.98	0.009	645 (u = 74%)	26	0.113 (u = 74%)	2.28	11.1	0.06	2.68
12	Control FTF	0.6320	60.25	--	0.96	0.007	--	--	--	2.18	--	0.33	2.90
14	Control FTF	0.6379	58.23	--	0.98	0.014	--	--	--	2.01	--	-0.41	2.10
15	90% PWP	0.6267	62.07	0.29	0.96	0.016	32 (u = 75%) 39 (u = 93%)	7	2.32 (u = 75%) 4.32 (u = 93%)	2.48	14.0	-0.68	3.11
16	100% PWP	0.6416	56.94	0.32	0.98	0.020	13 (u = 100%)	0	4.70 (u = 100%)	1.88	15.0	-0.10	2.64
17	Large strain test	0.6368	58.66	0.32	0.96	0.011	15 (u = 100%) 22 (2ε = 8.1%)	0	8.10	3.16	15.0	-0.03	2.13
18	High $\bar{\sigma}_c$ $\bar{\sigma}_c$ = 60 psi	0.6265	62.20	0.20	0.99	0.020	275 (u = 73%)	27	2.81	4.76	43.5	-0.01	1.68
19	High $\frac{\sigma_{dp}}{2\bar{\sigma}_c}$	0.6355	59.08	0.35	0.98	0.017	6 (2ε = 9.6%)	0	9.60	2.83	15.0	0.09	2.25
20	Monotonic load	0.6516	53.56	--	0.98	0.007	--	139	0.93	3.02	-5.8	-0.44	2.12
21	Monotonic load	0.6508	53.83	--	0.98	0.018	--	286	2.57	3.19	-27.9	0.80	3.67
22	Monotonic load	0.`596	50.78	--	0.98	0.019	--	435	3.03	3.49	-50.3	0.27	3.03
23	Monotonic load	0.6397	57.61	--	0.98	0.014	--	511	2.73	5.25	-61.7	0.06	2.36

(Continued)

(Sheet 1 of 4)

Table 1 (Continued)

Test No.	Purpose	Void Ratio After Test e_f	Average Relative Density After Test percent	Stress Ratio $\sigma_{dc}/2\sigma_c$	"B" Factor	ΔH During Freezing in.	Number Cycles N	σ_{3f}/σ_c percent	Peak-to-Peak Strain, ε_f percent	Standard Deviation After Test Percent Relative Density	Δ Pore Pressure $u_f - u_c$ psi	Skewness	Kurtosis
	Nominal 70 Percent Relative Density Tests - Wet Pluviation/Vibratory Table Compaction												
38	Control F	0.5880	75.43	--	--	--	--	--	--	2.55	--	-0.27	2.21
39	Control F	0.5910	74.34	--	--	--	--	--	--	2.99	--	-0.05	1.89
40	Control FTF	0.6100	67.86	--	0.98	0.008	--	--	--	3.03	--	-0.47	3.28
41	Control FTF	0.5994	71.43	--	0.96	0.018	--	--	--	3.03	--	-0.49	3.39
42	85% PWP	0.5960	72.68	0.27	0.98	0.010	8 (u = 85%)	15	1.14	3.22	12.8	0.45	2.45
43	100% PWP	0.6180	65.11	0.28	0.98	0.018	11 (u = 85%) 14 (u = 100%) 16 (2ε = 3.53%)	0	3.53	3.33	15.0	-0.22	2.44
44	Large strain	0.6249	62.76	0.27	0.98	0.007	10 (u = 85%) 13 (u = 100%) 25 (2ε = 9.64%)	0	9.64	4.87	15.0	0.45	2.47
45	Large strain	0.6262	62.28	0.29	0.98	0.007	6 (u = 85%) 8 (u = 100%) 16 (2ε = 9.81%)	0	9.81	5.38	15.0	0.52	2.29
46	Monotonic load	0.6225	63.58	--	0.96	0.020	--	349	3.87	4.04	-37.3	0.69	4.26
47	Monotonic load	0.5880	75.38	--	0.96	0.012	--	117	1.64	4.17	-2.6	-0.86	2.73
	Nominal 45 Percent Relative Density Tests - Wet Pluviation/Vibratory Table Compaction												
49	Control F	0.6940	38.99	--	--	--	--	--	--	3.23	--	0.51	2.48
50	Control F	0.6699	47.20	--	--	--	--	--	--	1.96	--	0.07	2.37
51	Control FTF	0.6710	46.91	--	0.99	0.020	--	--	--	2.49	--	-0.63	2.85
52	Large strain	0.6517	53.50	0.21	0.99	0.013	5 (u = 100%) 8 (2ε = 15.96%)	0	15.96	12.38*	15.0	-1.98	5.93
53	100% PWP	0.6758	45.22	0.22	0.99	0.008	4 (u = 96%)	4	2.57	5.42*	+14.4	-1.16	4.30

(Continued)

* Specimen preparation on vibratory table is believed to have caused specimen disturbance and consequently an initially nonuniform specimen.

(Sheet 2 of 4)

Table 1 (Continued)

Test No.	Purpose	Void Ratio After Test e_f	Average Relative Density After Test percent	Stress Ratio $\sigma_{dc}/2\bar{\sigma}_c$	"B" Factor	ΔH During Freezing in.	Number Cycles N	$\sigma_{3f}/\bar{\sigma}_c$ percent	Peak-to-Peak Strain, ε_f percent	Standard Deviation After Test Percent Relative Density	Δ Pore Pressure $u_f - u_c$ psi	Skewness	Kurtosis
Nominal 45 Percent Relative Density Tests - Wet Pluviation/Vibratory Table Compaction (Continued)													
54	Monotonic load	0.6781	44.42	--	0.99	0.008	--	149	3.77	6.37*	-7.4	-0.96	3.06
55	Monotonic load	0.6832	42.65	--	0.99	0.006	--	76	1.33	9.01*	3.6	-0.94	2.73
56	Monotonic load	0.6771	44.80	--	0.98	0.016	--	75	1.31	9.14*	3.8	-0.89	2.80
Moist Tamped 60 Percent Relative Density Tests													
57	Control FTF	0.6352	59.17	--	0.98	0.018	--	--	--	8.38	--	-0.17	2.79
58	Control FTF	0.6306	60.76	--	0.98	0.018	--	--	--	7.13	--	-0.07	2.29
59	100% PWP	0.6358	58.96	0.18	0.98	0.005	10 (u = 100%)	0	0.67	6.74	15.0	-0.35	3.14
60	100% PWP	0.6305	60.78	0.23	0.98	0.012	4 (u = 100%)	0	15.62	4.11	15.0	0.29	2.58
61	100% PWP	0.6321	60.24	0.13	0.96	0.014	41 (u = 100%) (2ε = 4.4%) 44 (2ε = 7.22%)	0	7.22	4.91	15.0	0.41	2.67
Nominal 40 Percent Relative Density Tests - Wet Pluviation/Indirect Impact Compaction													
62	Control FTF	0.6899	40.39	--	0.98	0.009	--	--	--	2.63	--	-0.33	2.18
63	Control FTF	0.6961	38.26	--	0.99	0.014	--	--	--	2.34	--	+0.48	1.77
64	100% PWP	0.6944	38.84	0.16	0.98	0 (Clamped)	11 (u = 100%)	0	0.60	3.02	15	0.38	1.97
66	100% PWP	0.6988	37.30	0.14	0.99	0 (Clamped)	47 (u = 100%)	0	1.62	2.46	15	-0.38	2.08
67	100% PWP	0.7002	36.85	0.15	0.99	0 (Clamped)	16 (u = 100%)	0	2.34	2.66	15	-0.77	2.95
68	Large strain	0.7184	30.59	0.15	0.99	0 (Clamped)	29 (u = 100%) (2ε = 3.18) 30 (2ε = 22.19)	0	22.19	11.81	15	-0.77	2.58

(Continued)

(Sheet 3 of 4)

Table 1 (Concluded)

Test No.	Purpose	Void Ratio After Test e_f	Average Relative Density After Test percent	Stress Ratio $\sigma_{dc}/2\bar{\sigma}_c$	"B" Factor	ΔH During Freezing in.	Number Cycles N	σ_{3f}/σ_c percent	Peak-to-Peak Strain, ε_f percent	Standard Deviation After Test Percent Relative Density	Δ Pore Pressure $u_f - u_c$ psi	Skewness	Kurtosis
			Nominal 40 Percent Relative Density Tests - Wet Pluviation/Indirect Impact Compaction (Continued)										
69/ 70	Composite	0.6608	50.36	0.15	0.99	0 (Clamped)	21 (u = 100%) 24 (2ε = 8.05%)	0	8.05	3.06	15	-0.63	3.66
(69)	Loose layer	0.70	38 (est)	--	--	--	--	--	--	2.6 (est)	--	--	--
(70)	Dense layers	0.65	53 (est)	--	--	--	--	--	--	2.3 (est)	--	--	--
						Initial Demonstration Tests of April 1980							
A	Control FTF	0.6106	67.62	--	0.96	--	--	--	--	3.21	--	-0.71	2.49
B	75% PWP	0.6176	65.21	--	0.97	--	--	--	--	3.35	--	-0.45	2.28

(Sheet 4 of 4)

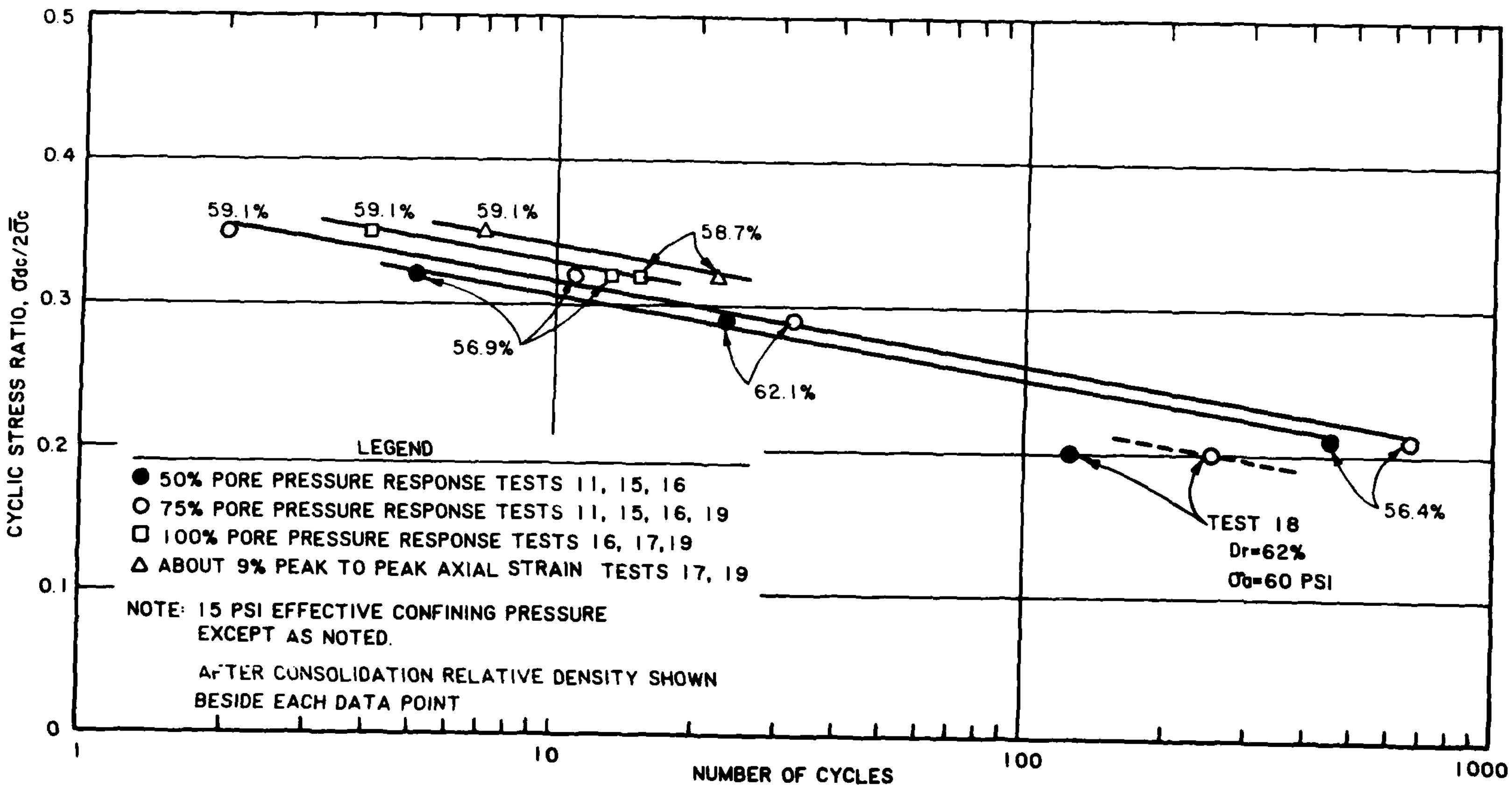

Figure 13. Summary of cyclic triaxial tests at nominal 60 percent average relative density

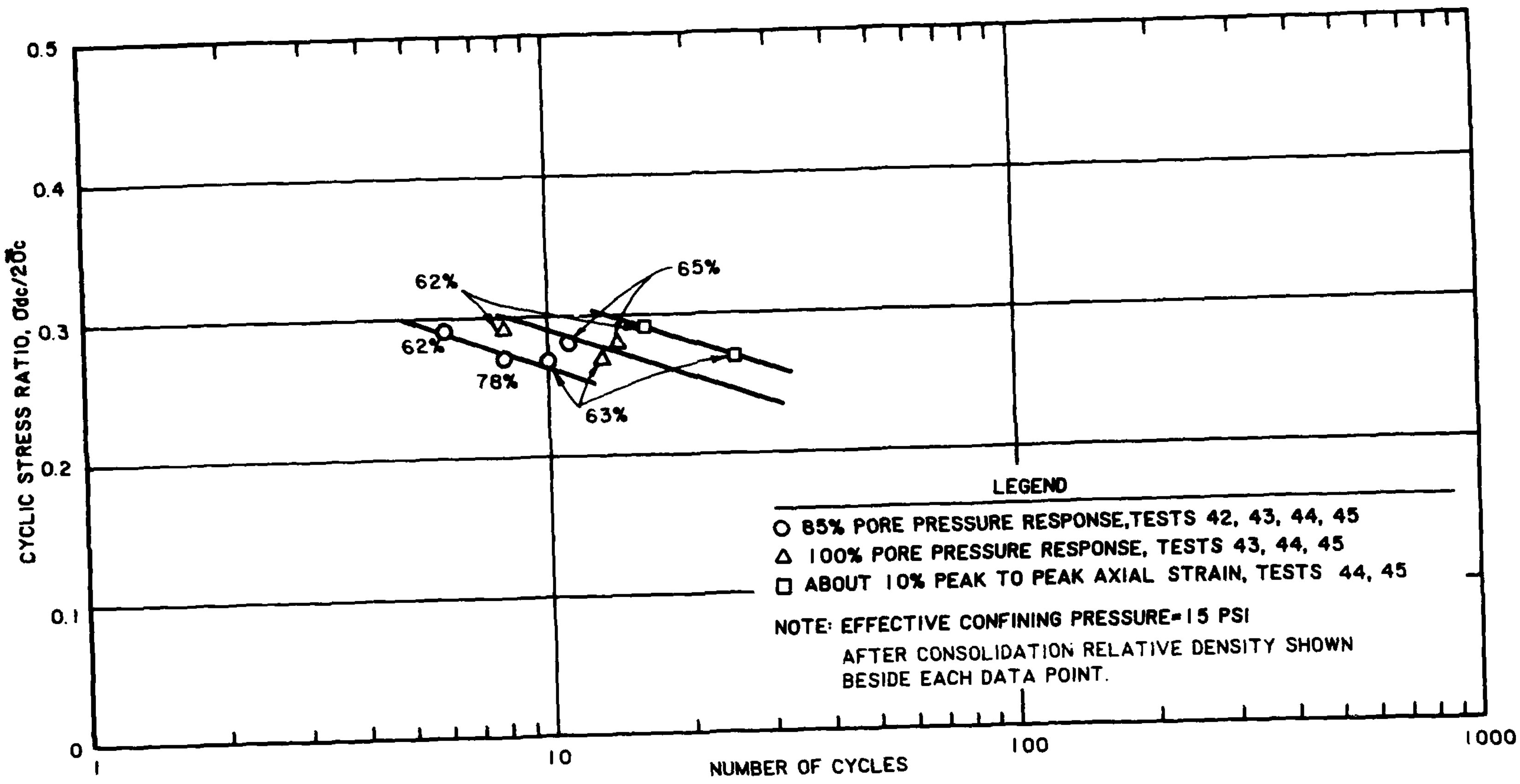

Figure 14. Summary of cyclic triaxial tests at nominal 70 percent average relative density

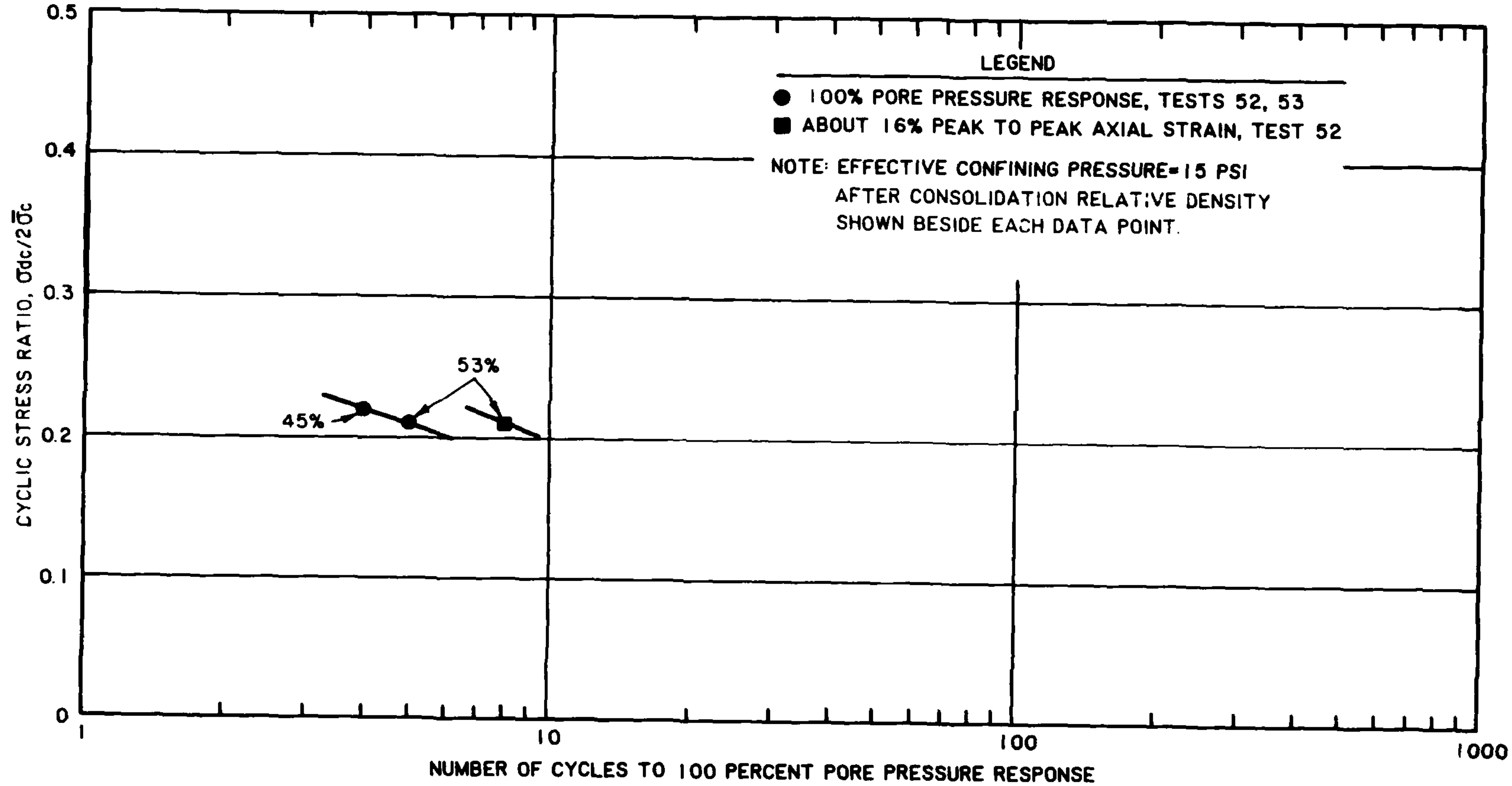

Figure 15. Summary of cyclic triaxial tests at nominal 45 percent average relative density

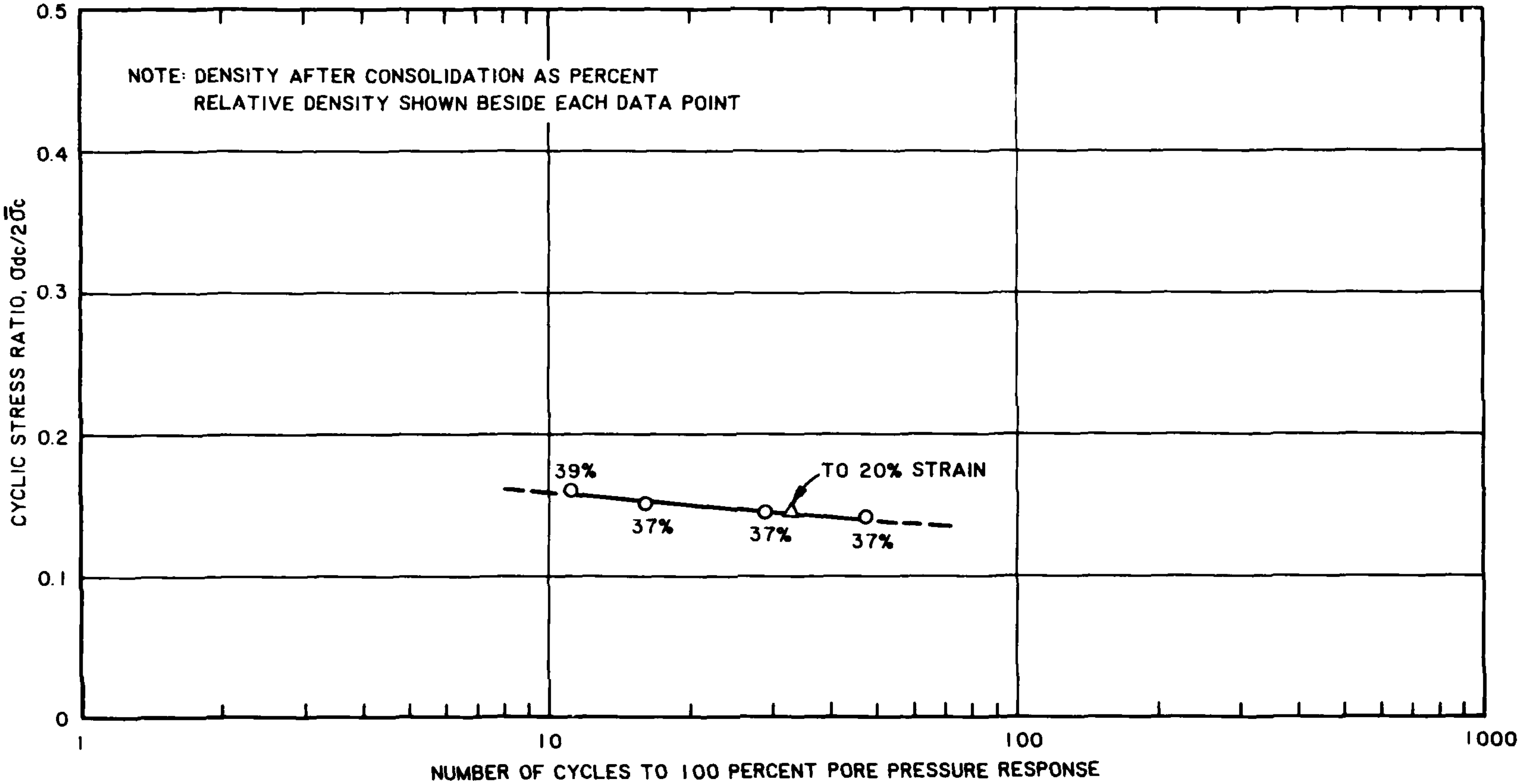

Figure 16. Cyclic triaxial tests on water-pluviated specimens at nominal 40 percent relative density

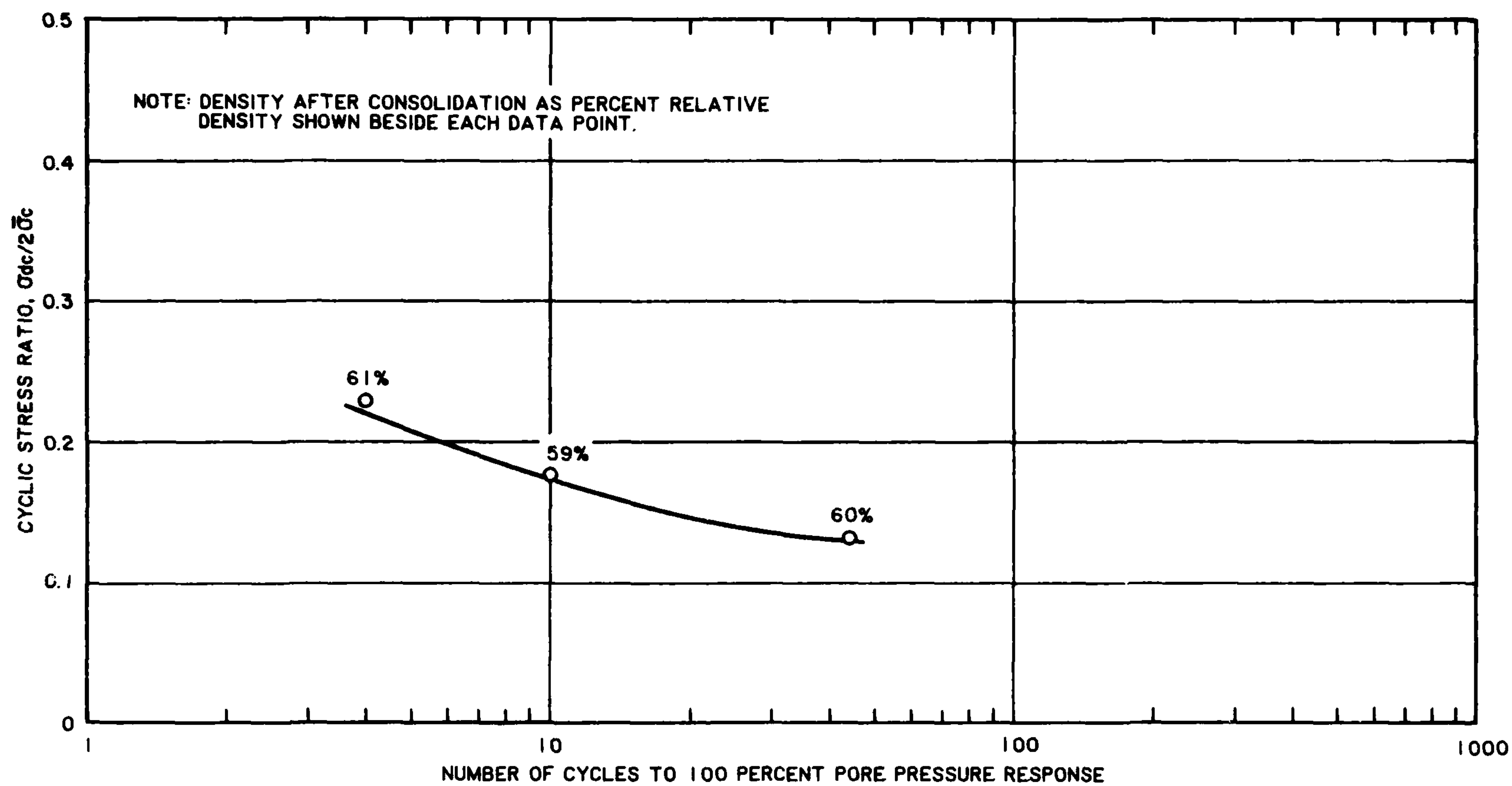

Figure 17. Cyclic triaxial tests on moist-tamped specimens at 60 percent relative density

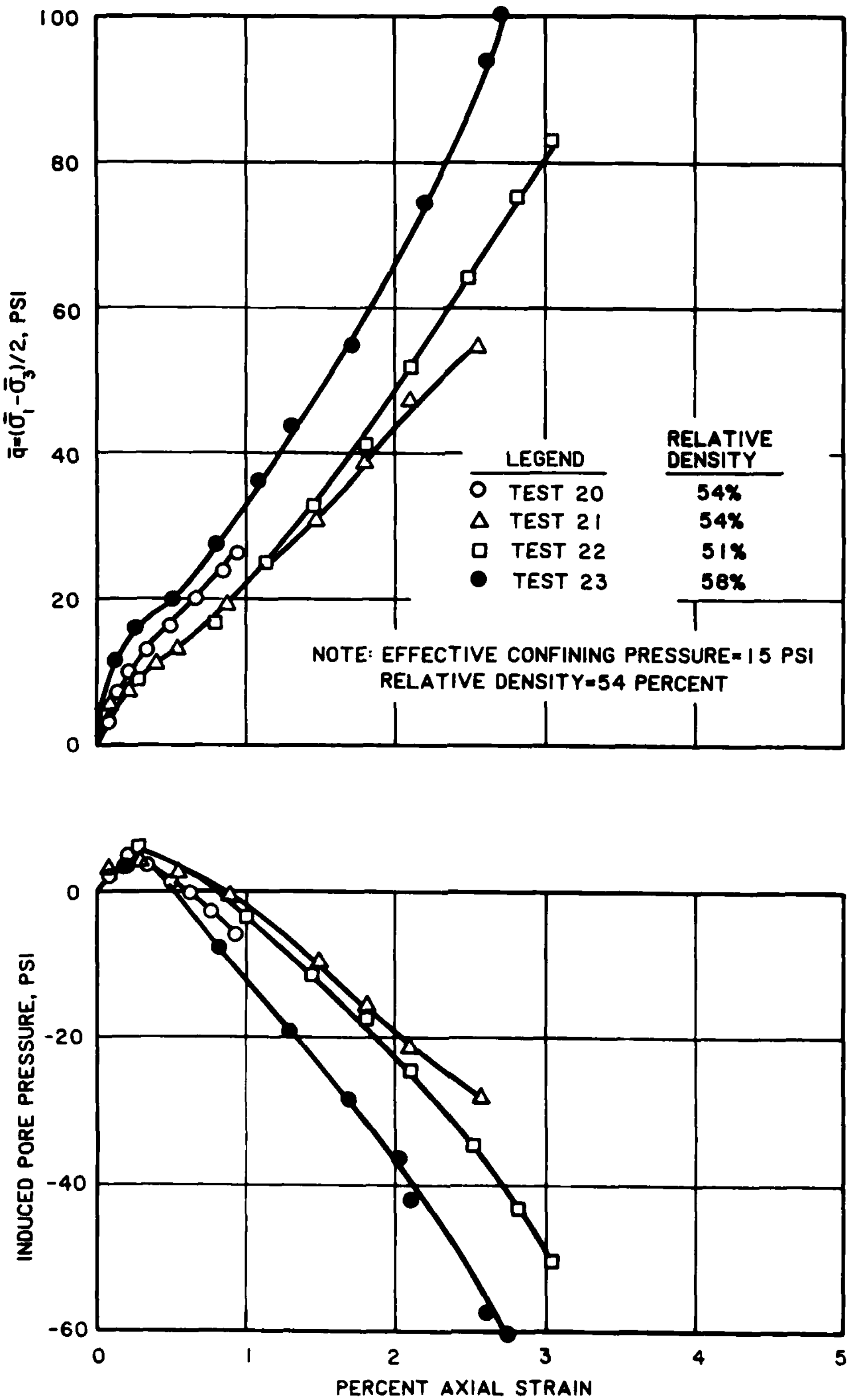

Figure 18. Specimen monotonic load response at nominal percent average relative density

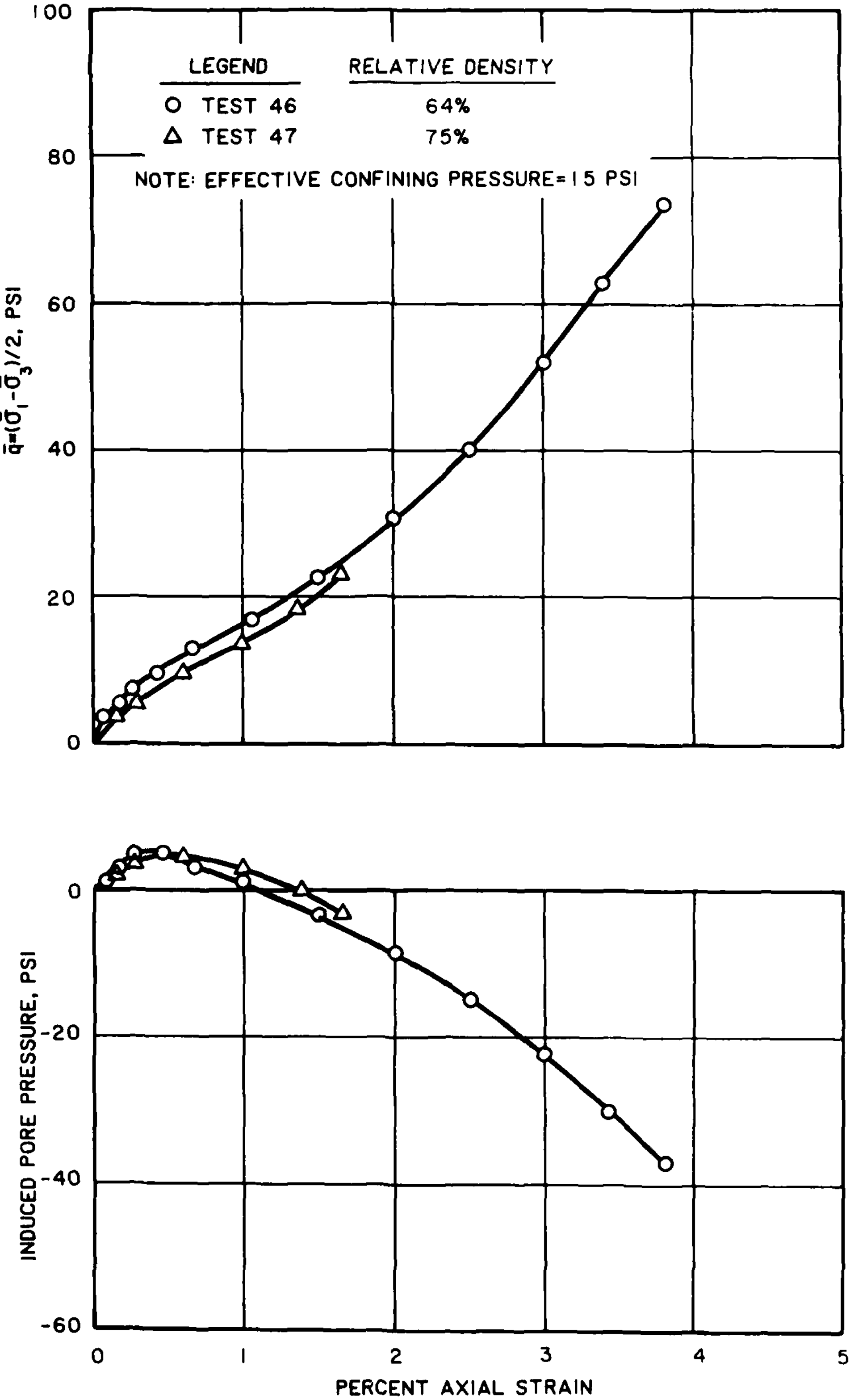

Figure 19. Specimen monotonic load response at nominal 70 percent average relative density

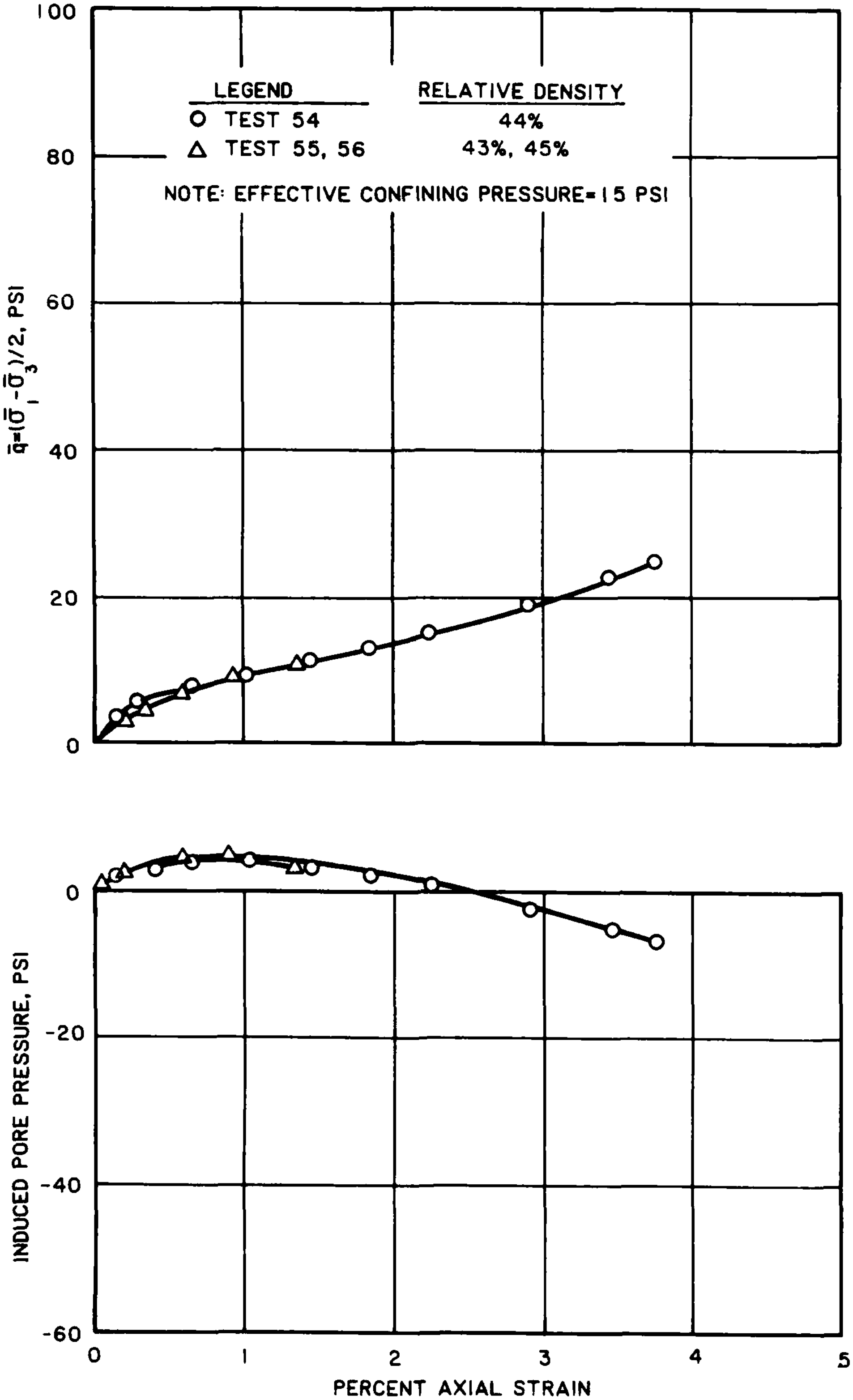

Figure 20. Specimen monotonic load response at nominal 45 percent average relative density

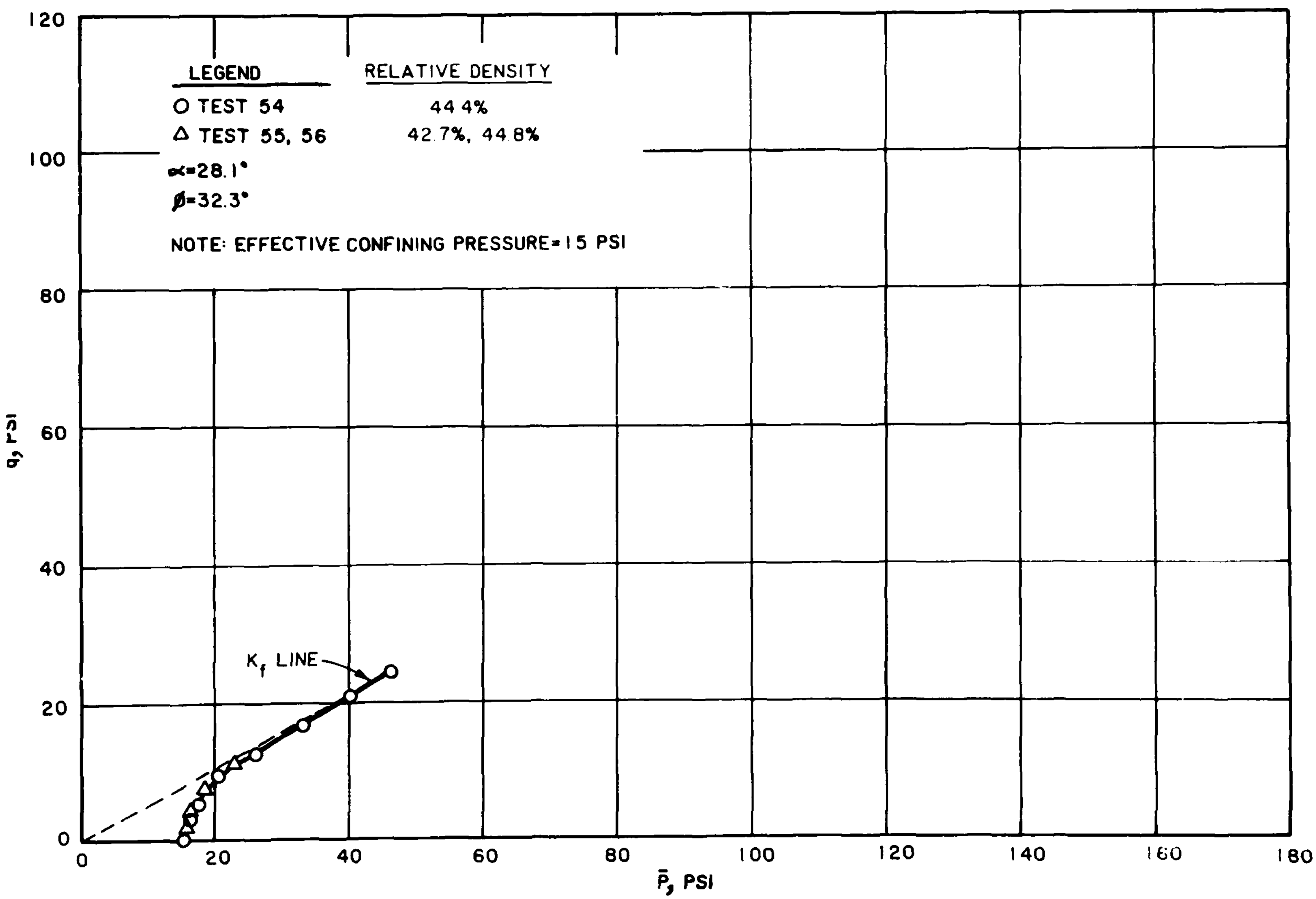

Figure 21. Specimen $\bar{p}$-$\bar{q}$ response at 44 percent average relative density

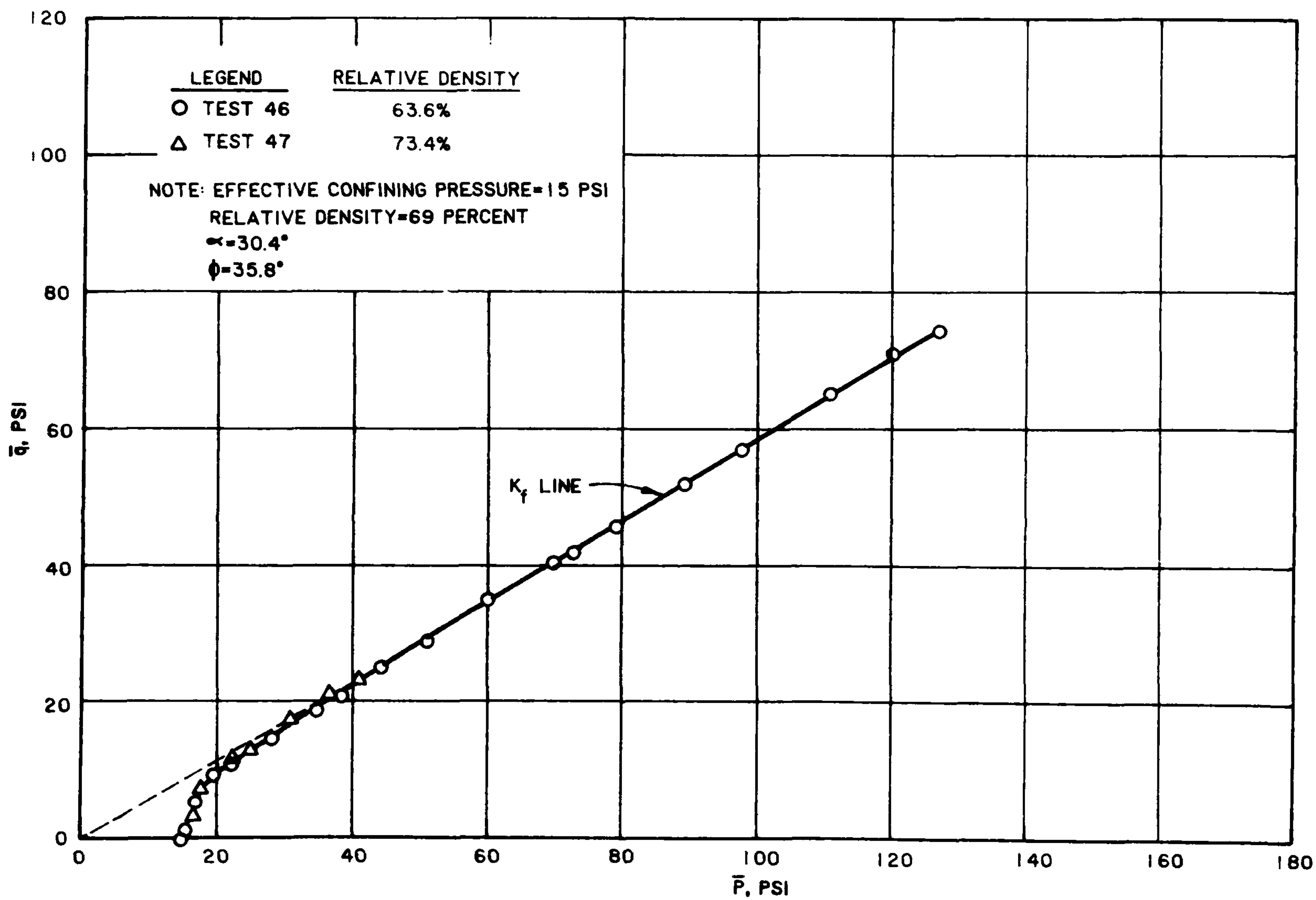

Figure 22. Specimen $\bar{p}$-$\bar{q}$ response at 69 percent average relative density

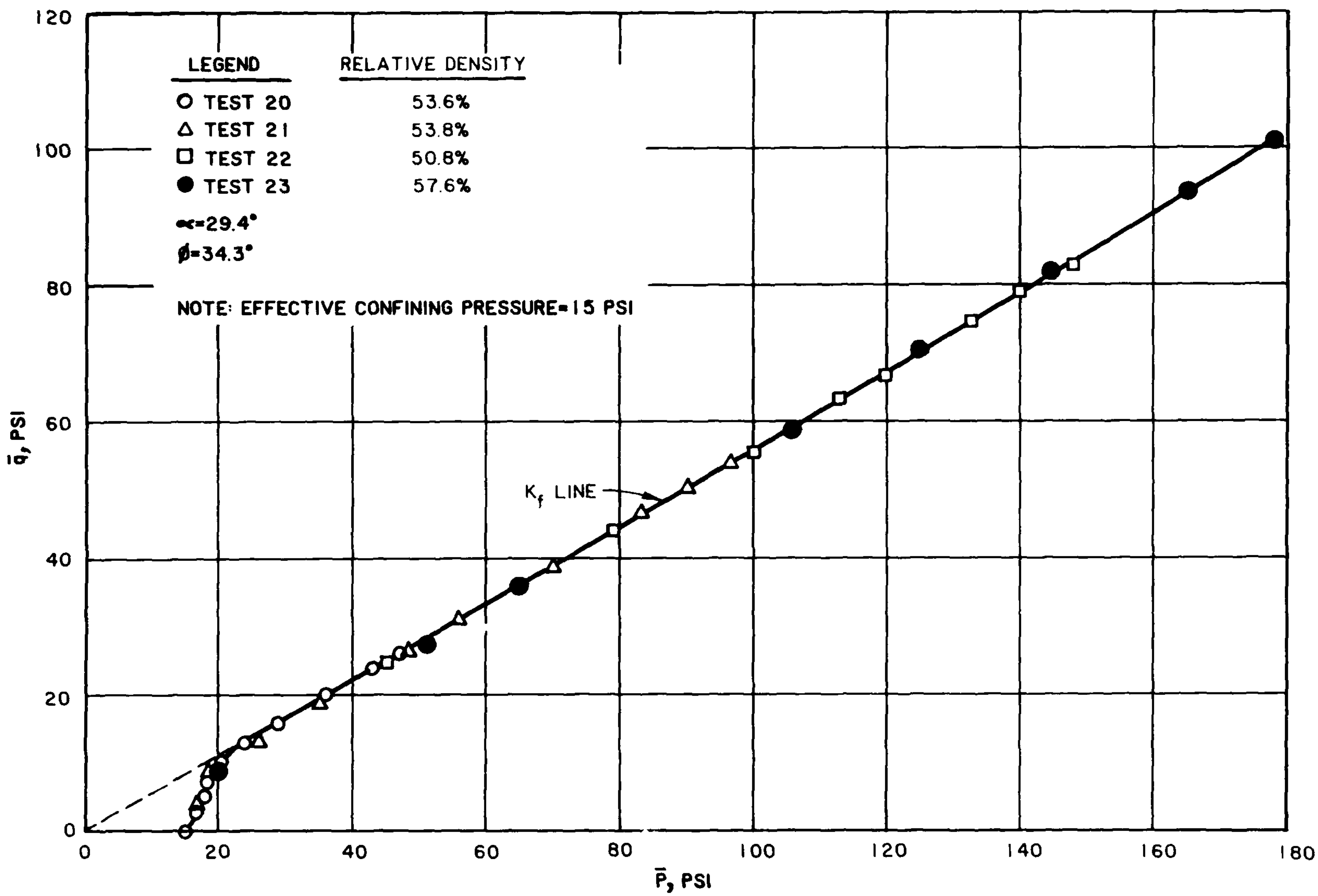

Figure 23. Specimen $\bar{p}$-$\bar{q}$ response at 54 percent average relative density

Table 2

Cyclic Load Test 11

$\bar{\sigma}_c = 15$ psi

$\sigma_{dc}/2\bar{\sigma}_c = 0.21$

Average relative density at the end of test = 56.36 percent

Average void ratio at the end of test = 0.6434

Cycle No.	σ_{dc} psi	Average Pore-Water Pressure psi	Pore-Water Pressure Bandwidth psi	Peak Pore-Water Pressure Response percent	Double Amplitude Strain percent
1	6.2	0	2.75	9.2	0.049
50	6.4	2.50	3.75	29.2	0.050
100	6.4	2.75	3.25	29.2	0.055
150	6.4	3.50	3.25	34.2	0.056
200	6.4	4.00	3.25	37.5	0.058
250	6.4	4.25	3.25	39.2	0.058
300	6.4	4.75	3.25	42.5	0.062
350	6.4	5.00	3.25	44.2	0.062
400	6.4	5.25	3.35	46.2	0.065
450	6.4	5.80	3.35	49.8	0.069
500	6.4	6.25	3.35	52.8	0.071
550	6.4	6.75	3.35	56.2	0.076
600	6.4	7.80	3.40	63.3	0.083
645	6.4	9.30	3.60	74.0	0.113

Table 3

Cyclic Load Test 18

$\bar{\sigma}_c$ = 60 psi

$\sigma_{dc}/2\bar{\sigma}_c$ = 0.20

Average relative density at the end of test = 62.20 percent

Average void ratio at the end of test = 0.6265 percent

Cycle No.	σ_{dc} psi	Average Pore-Water Pressure psi	Pore-water Pressure Bandwidth psi	Peak Pore-Water Pressure Response percent	Double Amplitude Strain percent
1	23.5	0	12.75	10.6	0.190
50	23.5	18.00	12.00	40.0	0.190
100	23.5	21.75	13.50	47.5	0.203
150	23.5	24.75	13.50	52.5	0.216
200	23.5	28.50	13.50	55.7	0.232
250	23.5	36.55	14.50	73.0	0.288

vibratory compaction being applied to the mold after pluviation was somehow resulting in an overconsolidated state which might be the cause of the surprisingly large number of cycles and the surprisingly little deformation experienced in Test 11. Previous cyclic tests on Banding sand (Castro 1969) had led to the expectation that at this stress ratio the specimen would be much more compliant.

66. Computer printout sheets showing density distribution analysis are shown in Appendix B for all the tests listed in Table 1. These sheets show the density distribution analysis by disc and column as well as the averages for the various discs and columns for specimens dissected in the pattern shown in Figure 11. Also included in this analysis are statistical parameters showing the variations in rows, columns, and the entire specimen or standard deviation. Included also in the analysis are the parameter skewness and kurtosis for the entire specimen.

PART IV: SPECIMEN BEHAVIOR

Cyclic Triaxial Tests

67. The behavior of specimens subjected to cyclic loading can be seen in the standard form of cyclic stress ratio versus number of cycles to various levels of pore pressure or axial strain in Figures 13 through 17. Typically, pore pressure increases with cyclic load application up to 100 percent response at relatively small axial strain. After 100 percent pore-pressure response, the axial strain increases rapidly up to the limit of the testing apparatus. Values of various test parameters are listed for Tests 11 and 18 in Tables 2 and 3 and the typical behavior of pore pressure or strain as cyclic loading continues is presented there. The pore-water pressure and double amplitude strain bandwidths were observed to increase with increasing numbers of applied cyclic pulses. Average pore-water pressure increased at an increasing rate as 100 percent response was approached. This was especially true at high stress ratios and made the task of arresting loading at 90 percent pore-pressure response in specimens under load at a frequency of 1 Hz somewhat uncertain. This point is demonstrated clearly in Figure 13. In Test 11 at a stress ratio of 0.21, 450 cycles were required to develop 50 percent pore-pressure response and an additional 225 cycles to increase the response to 75 percent. In Test 16 at a ratio of 0.32, 50 percent response occurred in 6 cycles with 75 percent occurring 4 cycles later and 100 percent response in 2 additional cycles. Figure 14 is the summary of cyclic triaxial tests at nominal 70 percent relative density which was molded or placed on the vibratory table. It should be noted that if a comparison of the tests at 70 percent is made with specimens of 60 percent relative density from Figure 13, the cyclic strength will be observed to be lower in the specimen of Figure 14 even though the density is higher. This is believed to be due to a higher degree of nonuniformity in the specimen at 70 percent nominal relative density caused by erratic operation of the vibratory table. (The specimens of Figure 13 were prepared by densifying with a drop hammer.) The difference in initial density uniformity is verified by comparing the control specimens prepared by densification with the drop hammer (specimens 12 and 14) with the control specimens prepared with the vibratory table (specimens 40 and 41). The average standard deviations are observed to be 2.10 percent and 3.03 percent relative density, respectively.

68. Specimens prepared at a nominal relative density of 45 percent were tested cyclically, and the results are shown in Figure 15. However, because a lower density was desired and because these specimens were also prepared on the vibratory table, it was decided to repeat this series of tests with about 40 percent relative density as the target and prepare the specimens by pluviating through water and densifying with the drop hammer.

69. Figure 16 is the summary of cyclic tests performed at about 40 percent relative density molded by wet pluviation and densified with the drop hammer. Figure 17 summarizes cyclic tests prepared by the more standard method of moist tamping. Figure 24 compares cyclic triaxial data on moist-tamped triaxial test specimens of Banding sand at about 60 percent relative density taken from the literature (Castro 1969) with the moist-tamped specimens at 60 percent prepared for this study. The results seem to compare favorably although the Castro tests were performed under 4 kg/cm^2 (57-psi) effective confining pressure and the tests for this investigation were performed under 15-psi pressure. Results of the very uniform specimens in Figure 13 are also shown in this figure and they are seen to be significantly stronger than either the specimens prepared and tested by Castro or the moist-tamped specimens of the present investigation. Specimens in this investigation tested to deformation levels where movement could be seen with the unaided eye were observed to deform smoothly with the specimen forming the characteristic "dog bone" shape in extension and the "barrel" shape in compression. No specimen was observed to neck or pull apart in this investigation.

Monotonic Triaxial Tests

70. The behavior of specimens subjected to monotonic loading can be seen in Figures 18 through 23. Dilative response was observed in all specimens tested in this mode, and the plots shown are indicative of dilative response. Figures 18, 19, and 20 show induced pore pressure and $\bar{q}$, which is one-half the deviator stress, plotted versus axial strain. The value of $\bar{q}$ increases monotonically with strain; induced pore pressure increases slightly, then begins to decrease, and decreases to higher negative values until loading is ended.

71. The $\bar{p}$-$\bar{q}$ plots shown in Figures 21, 22, and 23 are called stress paths. All specimens tested showed the typical kind of stress path behavior

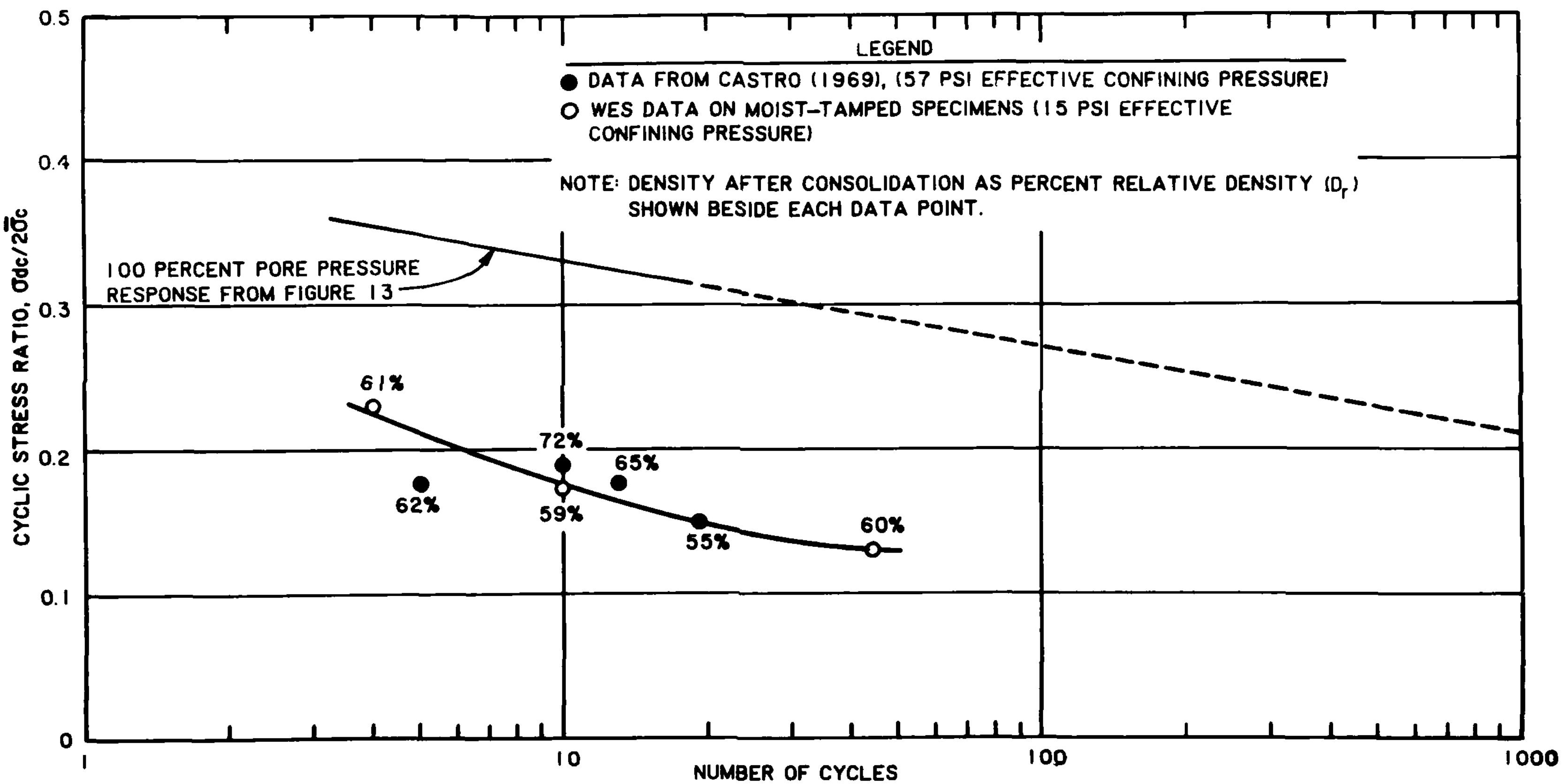

Figure 24. Comparison of cyclic triaxial tests on moist-tamped specimens at 60 percent relative density

which was called "dilative response" by Castro (1969) because the specimen was still dilating when the test was ended. The envelope of the $\bar{p}$-$\bar{q}$ plots is called the K_f line as described by Lambe and Whitman (1969). This envelope has slope α which is related to ϕ, the effective angle of internal friction, by the relationship

$$\sin \phi = \tan \alpha$$

72. The value of ϕ is somewhat dependent on density and this relationship is shown in Figure 25, with ϕ and relative density being taken from the monotonic loading tests performed at an effective confining pressure of 15.0 psi. Data taken from S triaxial tests performed by Castro (1969) at 1 kg/cm^2 are shown in this figure along with the data obtained during the present study. The combined data show the variation of friction angle, ϕ, with void ratio, e, over the range of data covered.

73. It should be noted that for the type of dilative response observed in these tests, points on the stress path tend to converge to the K_f line. This is, in fact, the behavior observed, as can be seen in Figures 21, 22, and 23. In these figures, all stress paths are seen to converge on each other and on the K_f line which passes through the origin of the plot. Small variations in density from specimen to specimen seem to affect stress path behavior very little. However, deviator stress and pore pressure response with axial strain are more affected by these variations as can be seen in Figures 18, 19, and 20.

74. Because these specimens were so highly dilative in response, loading could not be continued to produce large axial strains for the reason that pore-water pressure decreased so rapidly during loading that it was feared that low pore-water pressure would cause cavitation or loss of saturation. In either case, the associated specimen would have been lost since complete water saturation was necessary for posttest density distribution analysis.

Freezing Behavior

75. Specimens loaded cyclically were frozen with full compressive axial load applied when possible. This was not possible in cases where 100 percent pore-water pressure response had been reached and the strength of the specimen

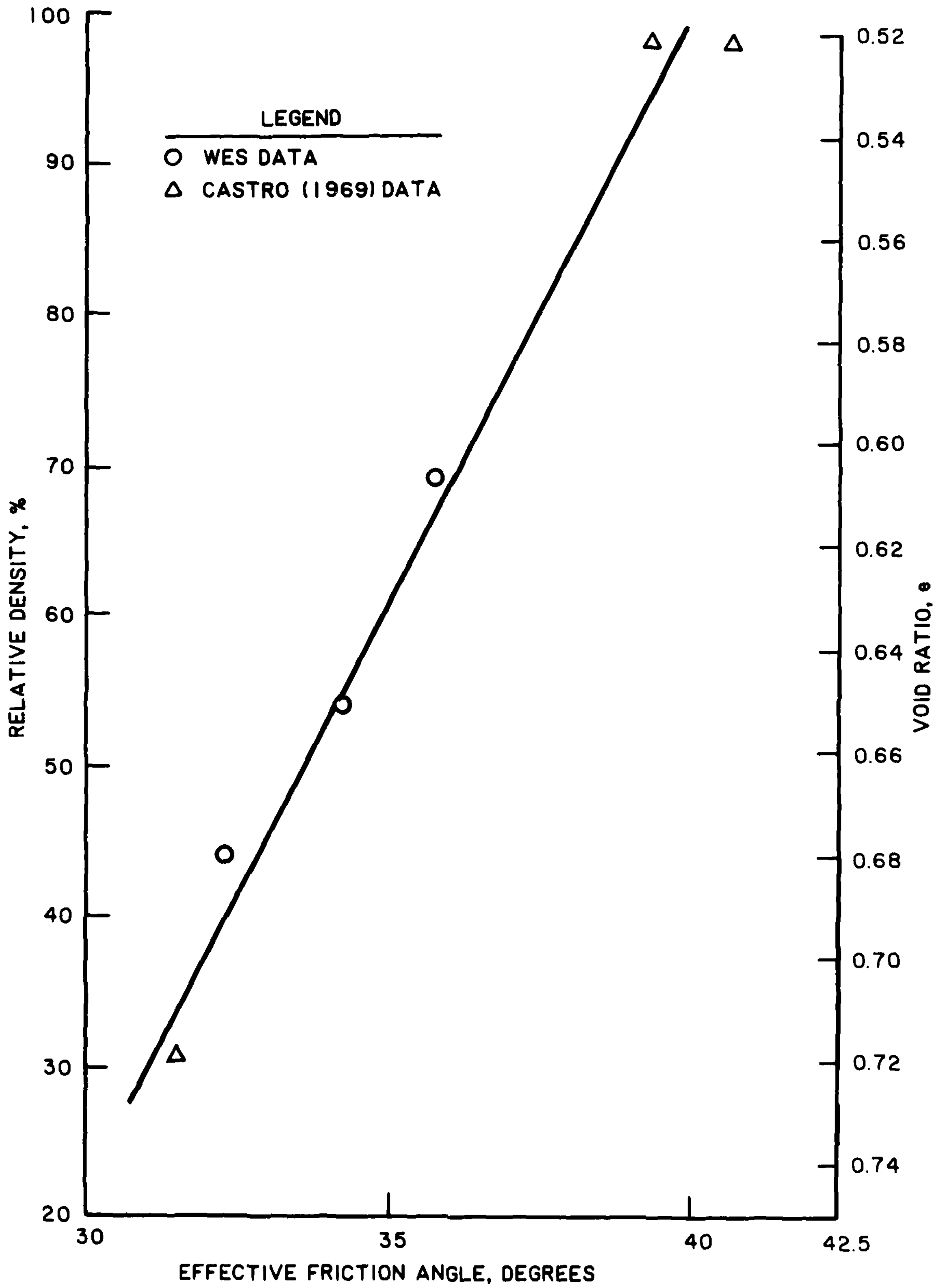

Figure 25. Relative density versus effective friction angle

had been significantly reduced. In those cases, specimens were frozen under a small (1- to 5-lb) compressive axial load. Settlement during freezing was monitored and was always less than 0.025 in.

76. Monotonically loaded specimens were frozen under the maximum applied compressive load, and effective stress in the dilated specimens was generally so high that little settlement or creep occurred.

Spatial Density Distribution

77. The spatial distribution of relative density is summarized in Tables 4 through 7, and Figures 26 through 30 for the tests performed. Computer-plotted contours are shown in Appendix C for all the specimens presented in Appendix B and show the density distribution in each of the specimens as relative density in 1-percent increments. Referring to Figure 11, two slices are taken through the specimens in the contour plots, a vertical slice through columns 3, 6, 7, and 10 and a vertical slice through columns 4, 5, 8, and 9. The two vertical sections are rotated about a "fold line" shown on all the figures of the appendix, and it should be noted that symmetry is to be expected between the two sections examined, and symmetry is roughly observed in the contour plots. The tables, figures, and contours suggest that there is no well defined pattern in the specimen.

78. Two spatial distributions will be examined for trends by the tables and plots--the density distribution in the axial direction, and the density distribution in the radial direction. It should be noted that the data in the tables that follow were obtained directly from the computer printouts of Appendix B. The entries under "Slab" shown on the tables are the differences between the average relative density of any slab within the specimen and the average relative density of the entire specimen. The last four columns on the tables are the average relative density of the eight peripheral elements 1 to 4 and 9 to 12, the average relative density of the interior elements 5 to 8, the relative density difference between the central and peripheral columns, and the standard deviation, repeated here for clarity and comparison.

Specimens at nominal 60 percent relative density

79. Specimens 10 through 23 were molded by pluviation through water and densified with a drop hammer to a nominal relative density of 60 percent. These tests are summarized in Table 4 and on Figure 26. The control specimens

Table 4

Spatial Distribution of Specimens at Nominal 60 Percent Relative Density

Test No.	Purpose	Relative Density Minus Average Relative Density for Specimen, percent								Average Relative Density Columns 1-4, 9-12 percent	Average Relative Density Columns 5-8 percent	Δ Relative Density percent	Standard Deviation in Specimens percent
		Slab											
		I	II	III	IV	V	VI	VII	VIII				
10	Control F	-0.84	-0.22	-0.82	0.98	1.04	1.05	-1.13	-1.03	58.56	56.63	1.93	1.67
12	Control FTF	-0.53	0.46	-1.11	2.44	0.08	0.19	1.25	-2.64	60.83	59.13	1.80	2.18
14	Control FTF	-1.80	1.55	1.95	1.58	-0.06	-1.62	-2.62	1.08	58.36	58.04	0.32	2.01
11	Cyclic test	3.38	1.90	0.11	0.13	-1.50	0.17	-1.08	2.63	55.99	57.28	-1.29	2.28
15	Cyclic test	-5.01	-0.40	0.42	1.87	1.40	1.52	0.18	1.84	62.34	60.85	1.49	2.48
16	Cyclic test	-3.05	-0.32	-0.69	0.24	0.62	1.79	1.43	-0.68	57.36	55.84	1.52	1.88
17	Cyclic test	-1.24	-1.33	-2.48	-2.39	-0.95	0.49	3.77	3.60	58.96	57.85	1.11	3.16
19	Cyclic test	-2.01	-1.49	-2.62	-1.83	-0.65	2.15	3.76	1.63	59.59	57.67	1.92	2.83
20	Monotonic test	-0.55	-1.23	-0.39	-0.25	-0.77	-0.37	1.46	-0.26	54.97	49.86	5.11	3.02
21	Monotonic test	-1.65	-1.27	-2.26	-0.41	0.50	3.59	1.19	-2.29	54.67	51.18	3.49	3.19
22	Monotonic test	4.26	3.79	-0.18	-2.45	-3.02	-1.74	-0.62	-1.71	51.66	48.41	3.25	3.49
23	Monotonic test	3.02	-4.01	-3.00	-2.19	-0.12	3.77	2.58	1.07	59.76	51.46	8.31	5.25

Table 5

Spatial Distribution of Specimens at Nominal 70 percent Relative Density

Test No.	Purpose	Relative Density Minus Average Relative Density for Specimen, percent — Slab I	II	III	IV	V	VI	VII	VIII	Average Relative Density Columns 1-4, 9-12 percent	Average Relative Density Columns 5-8 percent	Δ Relative Density percent	Standard Deviation in Specimens percent
38	Control F	0.77	1.67	0.18	-0.78	-0.90	-1.10	0.72	0.61	73.93	78.21	-3.95	2.55
39	Control F	-2.46	-2.62	-0.38	1.19	1.13	1.01	2.10	0.46	73.28	76.62	-3.34	2.99
40	Control FTF	-3.94	0.13	-1.15	0.46	0.53	1.96	2.72	0.00	66.60	70.66	-4.06	3.03
41	Control FTF	-3.98	-0.28	0.92	1.52	0.85	0.66	1.06	0.51	69.99	74.78	-4.80	3.03
42	Cyclic test	1.87	2.85	1.29	2.98	-1.49	-0.74	1.15	-0.17	71.16	76.40	-5.24	3.22
43	Cyclic test	-2.88	0.61	0.95	-0.54	-0.48	-1.27	2.34	1.32	63.42	68.52	-5.10	3.33
44	Cyclic test	-1.58	-4.70	-3.38	-1.66	-0.82	1.31	4.31	7.40	61.60	65.40	-3.80	4.87
45	Cyclic test	-0.67	-3.94	-4.74	-3.00	-1.17	1.31	5.72	8.65	61.23	65.18	-3.95	5.38
46	Monotonic test	4.51	-2.71	-3.13	-3.08	-2.39	1.43	3.08	3.23	62.91	65.28	-2.37	4.04
47	Monotonic test	-4.80	-5.82	-1.67	1.55	2.39	3.51	3.25	2.24	74.31	77.78	-3.47	4.17

Table 6

Spatial Distribution of Relative Density in Moist-Tamped Specimens at 60 Percent Relative Density

Test No.	Purpose	Relative Density Minus Average Relative Density for Specimens, percent — Slab I	II	III	IV	V	VI	VII	VIII	Average Relative Density Columns 1-4, 9-12 percent	Average Relative Density Columns 5-8 percent	Δ Relative Density percent	Standard Deviation in Specimens percent
57	Control FTF	-2.19	8.80	0.68	-0.25	4.18	-2.87	1.43	-6.41	55.59	67.60	-12.01	8.38
58	Control FTF	-5.30	1.20	-0.82	5.01	6.50	3.77	-1.40	-5.57	57.56	68.44	-10.89	7.13
59	Cyclic test	-0.85	-2.37	2.97	3.90	7.51	-2.77	0.08	-5.74	56.19	65.51	-9.33	6.74
60	Cyclic test	0.07	3.34	0.23	5.30	1.07	-2.16	-1.88	-6.25	59.60	63.04	-3.44	4.11
61	Cyclic test	-1.77	-1.66	1.86	7.00	1.16	0.79	-3.83	-1.93	58.20	64.93	-6.73	4.91

Table 7

Spatial Distribution of Relative Density in Specimens at Nominal 40 Percent Relative Density

Test No.	Purpose	Relative Density Minus Average Relative Density for Specimens, percent — Slab I	II	III	IV	V	VI	VII	VIII	Average Relative Density Columns 1-4, 9-12 percent	Average Relative Density Columns 5-8 percent	Δ Relative Density percent	Standard Deviation in Specimens percent
62	Control FTF	-3.55	0.79	1.31	1.40	2.23	1.57	-1.86	-2.30	41.20	38.62	2.58	2.63
63	Control FTF	-1.84	-1.69	-0.80	0.95	1.27	1.66	0.16	-0.95	39.10	36.11	2.99	2.34
64	Cyclic test	-3.94	-1.38	-0.09	1.79	1.47	1.76	0.76	-2.15	39.81	36.24	3.56	3.02
66	Cyclic test	-4.14	0.26	2.31	0.23	0.24	0.34	1.74	-2.99	37.53	36.09	1.44	2.46
67	Cyclic test	-4.15	-1.59	0.18	1.83	1.70	1.47	1.27	-0.99	36.85	36.62	0.23	2.66
68	Cyclic test	-17.25	-15.76	-4.10	3.57	4.92	6.03	9.69	10.20	33.61	28.64	-4.97	11.81
69/70	Composite test	-4.57	-0.56	0.35	-1.95	1.92	1.79	2.08	0.53	50.98	48.95	-2.03	3.06

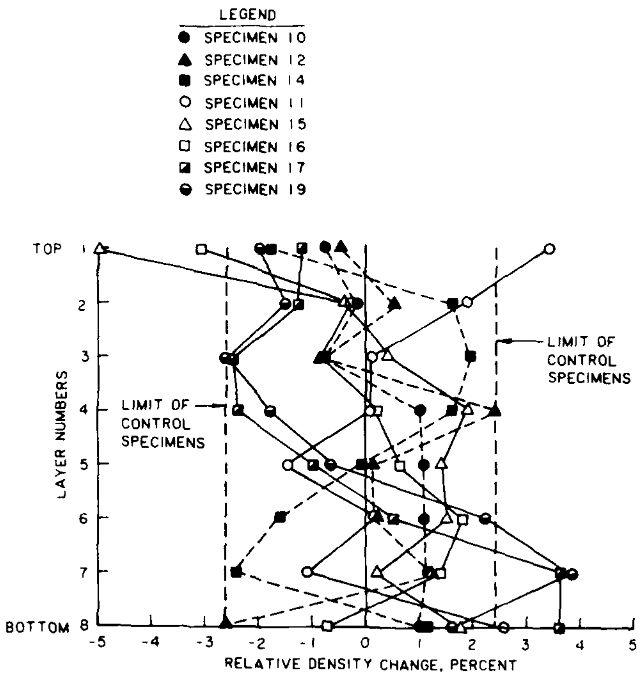

Figure 26. Relative density versus height in cyclically loaded specimens at nominal 60 percent relative density

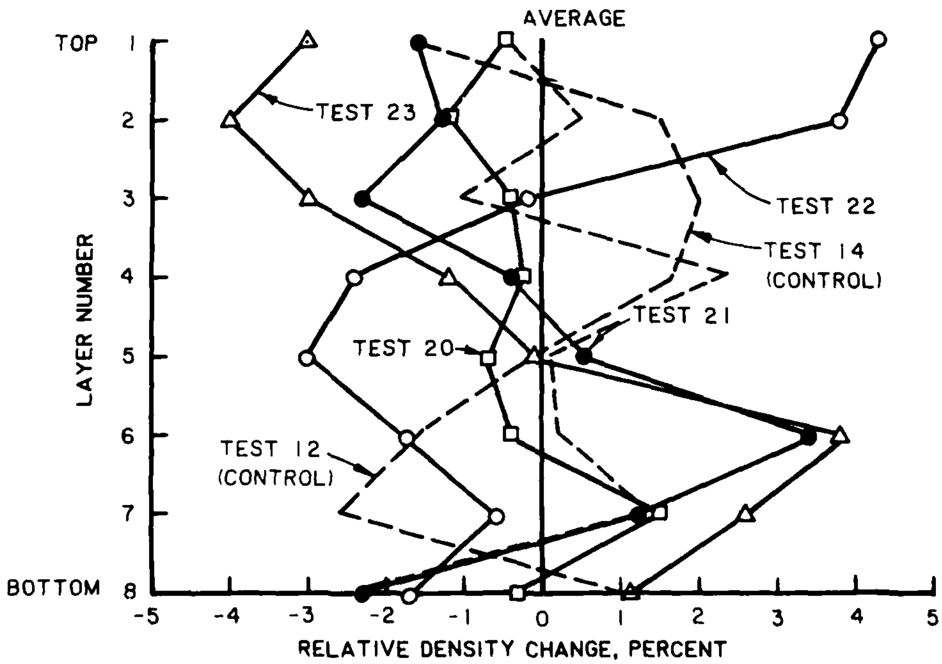

Figure 27. Relative density versus height in monotonically loaded specimens at nominal 60 percent relative density

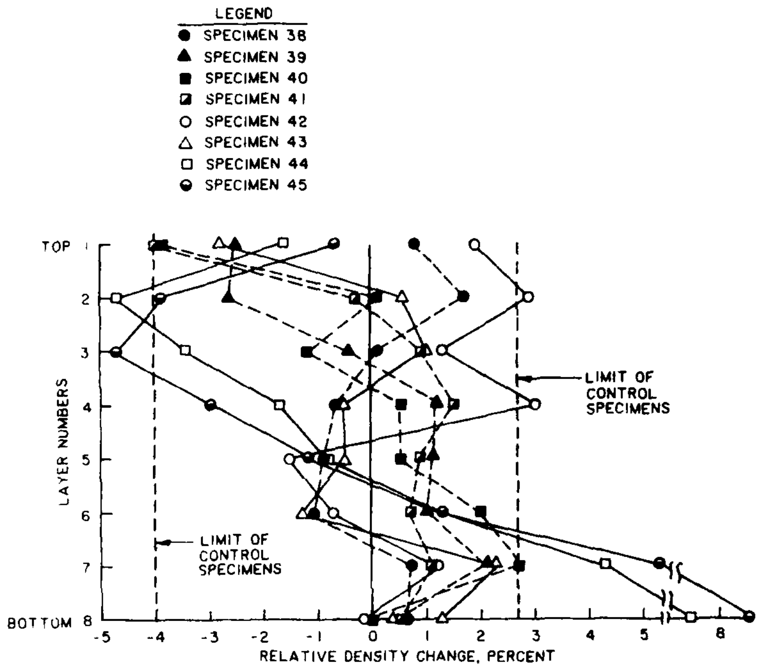

Figure 28. Relative density versus height in cyclically loaded specimen at nominal 70 percent relative density

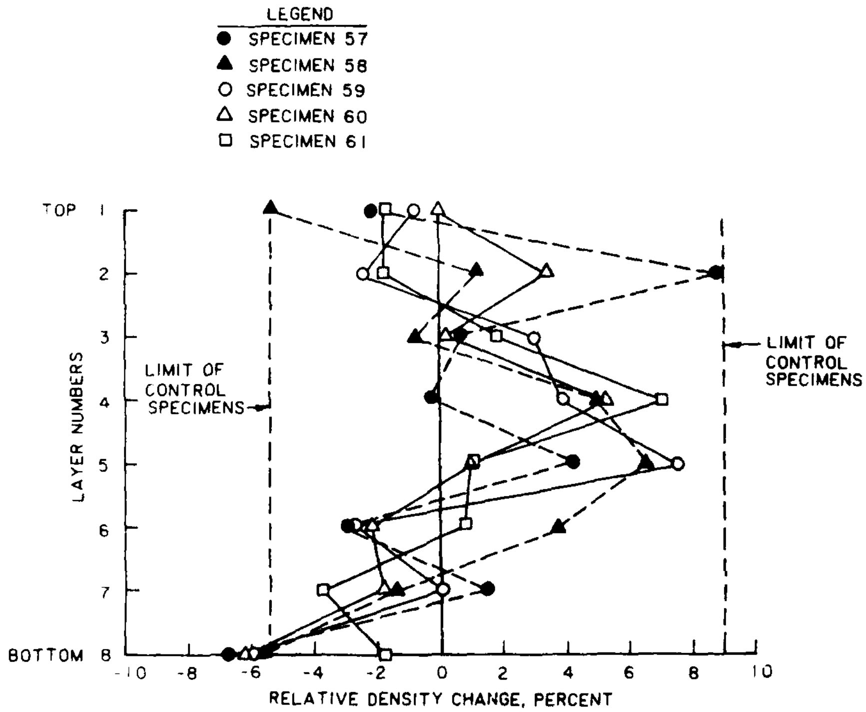

Figure 29. Relative density versus height in cyclically loaded specimens at 60 percent relative density formed by moist tamping

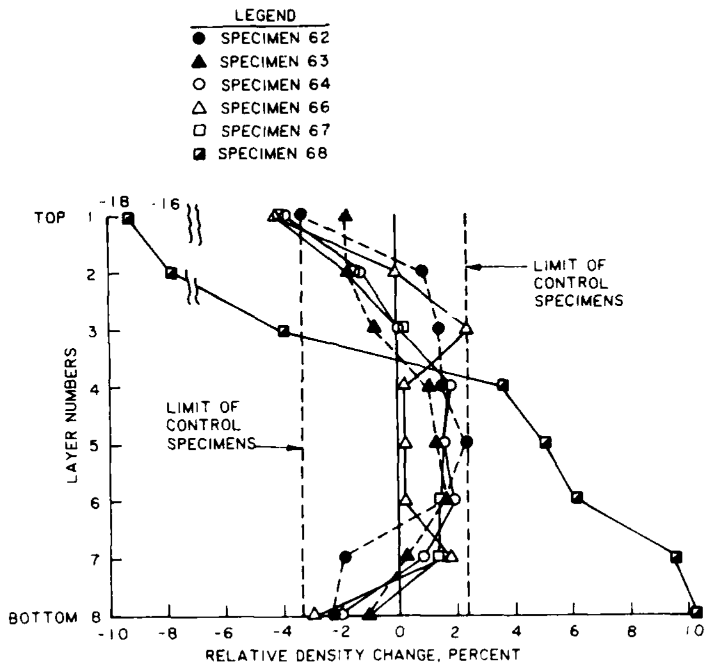

Figure 30. Relative density versus height in cyclically loaded specimens at nominal 40 percent relative density

are 10, 12, and 14. No identifiable trend can be seen in the vertical distribution shown in the entries under slab number for these control specimens, but there appears to be a measurable difference in relative density between the center columns and the peripheral columns of the specimen, the center column being apparently lower in relative density.

80. Specimens 11, 15, 16, 17, and 19 were subjected to cyclic loading before freezing, dissection, and analysis. The spatial trends in the vertical direction show larger deviations from the average relative density. The standard deviations are somewhat larger than in the control specimens; that is, the specimen became less homogeneous as a result of cyclic loading. Except for specimen 11, the center columns of all these specimens are at a lower relative density than the peripheral columns.

81. Specimens 20, 21, 22, and 23 were loaded monotonically and are shown plotted on Figure 27. The trend in these specimens is similar; an apparently random vertical pattern in the specimen, but larger difference between center and peripheral columns than in the control specimen, and a higher overall standard deviation after loading.

Specimens at nominal 70 percent relative density

82. Specimens 38 through 47, as shown in Table 5 and in Figure 28, were molded by pluviating through water and then densified by vibrating on a vibratory table. The standard deviations of the control specimens are higher than those of the previous specimens, indicating lower initial uniformity. There is also an identifiable radial pattern of density distribution within these specimens but opposite to the 60 percent relative density specimens. In these specimens, the outer columns are 3 to 5 percent looser than the central columns. There is no vertical pattern, however, except that as the standard deviation increases, the differences between the average specimen density and individual slab densities increase. Monotonically loaded specimens show patterns similar to cyclically loaded specimens.

Moist-tamped specimens at 60 percent relative density

83. Only control specimens and cyclically loaded specimens were tested at this molding condition. Five specimens were tested, specimens 57 through 61, and the results are summarized in Table 6 and in Figure 29. A target average density could be achieved quite precisely using the technique of moist tamping, but it can be seen by comparing the standard deviations of these control specimens shown in Table 6 with others (especially the control specimens in Table 4) that these were some of the most nonuniform specimens achieved during the investigation. There is no identifiable vertical pattern in these specimens; however, the central columns of the control specimen are seen to be denser than the peripheral columns by 11 to 12 percent relative density in these tamped specimens. Upon cyclic loading, this difference appears to decrease and the standard deviation correspondingly decreases from the initial (as-molded) condition; that is, the specimens become more homogeneous as a result of cyclic loading.

Specimens at nominal 40 percent relative density

84. These specimens were molded by pluviation through water and then densified by a falling weight in a manner identical to the water-pluviated specimen at 60 percent relative density. However, the energy applied by the falling weight was adjusted to achieve the desired lower density. As can be seen in Table 7 and in Figure 30, these specimens show the same radial pattern

of loose central columns and denser peripheral columns as the water-pluviated specimens at 60 percent relative density. This observation suggests that the radial pattern in triaxial specimens is a function of molding procedure used, and that water pluviation and indirect impact compaction produce uniform specimens (remember that 1 percent relative density represents a mass density of about 0.17 pcf in Banding sand) but introduce a measurable radial density pattern within the specimen. It should be stated, however, that other molding procedures tried in this investigation introduced more severe radial patterns and did not produce specimens nearly as uniform as wet pluviation with indirect impact compaction. No vertical pattern can be seen in these specimens at 40 percent relative density, except in specimen 68 which was cyclically loaded to a double amplitude strain of over 22 percent. Here a pattern is seen going from much looser than the average at the top (-17.25 percent difference between averages) to much denser than average at the bottom (+10.20 percent difference). Thus it appears that systematic density redistribution is seen in loose specimens loaded to large axial strain.

Composite specimens

85. A composite specimen was constructed to investigate behavior in a specimen of controlled nonuniformity. This was done because it was envisioned that many real-world alluvial sand deposits consist of thin beds deposited under different flow conditions, and significant density nonuniformity is expected over vertical distances of 1 in. or so. The specimen was constructed from two uniform specimens. Both specimens were constructed by the pluviation through water technique and were frozen and lathed to the appropriate size. The two uniform specimens were about 53 and 38 percent relative density, respectively, based on volumetric measurements of the total specimens. The fourth layer from the top was removed from the 53 percent specimen, and the fourth layer from the 38 percent specimen inserted in its place. The specimen was then installed in the triaxial chamber and cyclically loaded to 100 percent pore-pressure response. The initial relative density uniformity of the 38 and 53 percent relative density layers based on experience with control specimens was about 2.6 and 2.3 percent standard deviations, respectively. The initial standard deviation of the composite specimen is estimated to be about 6.4 percent relative density percentage points obtained by assuming that the dense layers of the specimen (I, II, III, V, VI, VII, and VIII) had exactly the same density and density distribution as the corresponding layers

of specimen 14 except lowered by 5 percent. (This would make the density of that part of the specimen 53.23 percent relative density.) The loose layer (IV) was assumed to have the same density distribution as the fourth layer of specimen 63 (39.21 percent relative density). The average density and standard deviation were then computed for this equivalent "composite" specimen. After cyclic loading at a cyclic stress ratio $\sigma_{dc}/\bar{\sigma}_c = 0.15$ to 100 percent pore-pressure response in 21 cycles and 8.1 percent peak to peak axial strain in 24 cycles, the standard deviation was 3.06 percent relative density percentage points. The behavior of this specimen demonstrates that density redistribution does occur since the standard deviation went from an estimated initial value of about 6.4 to 3.06 percent at 8.1 percent strain. This conclusively demonstrates redistribution even though the mechanism served to render the specimen more uniform upon cyclic loading. It also suggests that redistribution may be occurring in the field over distance scales measured in inches as a result of earthquake loading. The composite test specimen is shown as specimen 69/70 in Table 7. The loose inserted layer is layer 4 (IV), which is shown to be -1.95 relative density points below the average. It is believed that this layer started at about -12 relative density points below the average, so substantial redistribution has occurred, both in this loose layer and in the other layers of this specimen. The strength of the composite specimen is between the strength of uniform specimens at 60 percent relative density at about 9 percent peak-to-peak axial strain (Figure 13) and the strength of uniform specimens at about 38 percent relative density (Figure 16). The cyclic stress ratio required to produce 9 percent peak-to-peak strain in 21 cycles from Figure 13 is about $\sigma_{dc}/2\bar{\sigma}_c = 0.33$. From Figure 16 the cyclic ratio required to produce liquefaction and strain is only slightly higher than $\sigma_{dc}/2\bar{\sigma}_c = 0.15$. Therefore the strength of the composite is much closer to the strength of the weak layer.

Contours

86. The contours of density within the specimen shown in Appendix C help to demonstrate the absence of a consistent identifiable pattern in the specimen, but show patterns in specimens due to placement and loading. There is obviously a correlation between standard deviation (uniformity) and "closeness of spacing" of the contour lines in the figures. Very uniform specimens

such as control specimens and those loaded to very limited responses generally show a pattern of uniform and loosely spaced density contours within the specimen. Whereas specimens loaded to high axial strains, specimens placed by a procedure which did not ensure uniformity, or those specimens which were suspected of being disturbed by the placement procedure (placement on the shaking table) show closely spaced and irregularly spaced density contours, which indicate rapidly changing density gradients and density uniformity.

87. It should be mentioned that specimens 57 and 58 were moist-tamped and placed with an apparent density gradient increasing in magnitude toward the top of the specimen. It is to be noted that whereas these specimens were analyzed to be nonuniform relative to water-pluviated specimens, the density gradient placed in the specimen during compaction could not be detected after placement. This indicates that the method was successful in dispersing the compactive energy due to the changing stiffness of the specimen as the number of layers and consequently the specimen length increases.

Discussion

88. Because specimens 52 through 56 were molded by vibrating on a vibratory table after pluviation through water and because the table was later determined to operate erratically, the initial uniformity condition in these specimens is somewhat uncertain. These results will be presented in Appendix B, but should be regarded as questionable, especially since specimens of low relative density are more prone to disturbance than specimens at a higher relative density.

89. One of the major implications of these investigations is that the more uniform sand specimens are, the stronger and more stable they are against cyclic loading and the more dilative they are against monotonic loading. A comparison of the cyclic loading response of very uniform specimens prepared by wet pluviation against less uniform specimens prepared by moist-tamping is shown in Figure 24. Both series of specimens are prepared at approximately 60 percent relative density, yet a cyclic stress ratio of 0.18 will cause 100 percent pore-pressure response in 10 cycles in the less uniform moist-tamped specimens in Figure 24, while the same stress ratio would require more than 1,000 cycles to cause 100 percent response in the highly uniform water-pluviated specimens summarized in Figure 13. Specimens at about 40 percent relative density

molded by the technique of pluviation through water and summarized in Figure 16 are believed to be quite uniform. They are seen to possess approximately the same resistance to cyclic loading as moist-tamped specimens at about 60 percent relative density (Figure 17) at a stress ratio of about 0.15, both reaching 100 percent pore-water pressure response in about 20 cycles.

90. The uniform monotonic specimens at 54 percent relative density of Figure 18 (prepared by wet pluviation and densification by indirect impact compaction) are more dilative than the less uniform specimens at 69 percent relative density of Figure 19 (prepared by wet pluviation and densification on the vibratory table), dilativity being measured by the amount of negative pore-water pressure which develops with axial strain. Redistribution can be demonstrated to occur in the molded sand specimens beginning from both very uniform and very nonuniform states. In evaluating the cyclic loading response of the very uniform specimen prepared at 60 percent relative density by wet pluviation and the very nonuniform specimens prepared at 60 percent by moist tamping, redistribution can be observed to occur. The as-prepared bandwidths of both the initially uniform and nonuniform specimen are shown in Figure 31. As strain occurs, the initially uniform specimen becomes more nonuniform; whereas, with strain, the nonuniform specimen becomes more uniform. There is the suggestion here that between these two bandwidths, there will be a terminal degree of nonuniformity (in the specimens at 60 percent relative density) if enough axial strain is applied. What this diagram irrefutably demonstrates is that density redistribution does occur as a result of cyclic loading in triaxial test specimens. Whether or not this amount of redistribution is enough to render physical properties measured in the test invalid is not resolved by this research. However, by plotting the same index of uniformity for monotonic load tests against axial strain, it can be seen that at least for small strains, there appears to be more redistribution in the monotonic load test than in the cyclic triaxial test (Figure 32). It should be noted that despite this redistribution there is a strong empirical basis for the safe use of laboratory-determined R and $\bar{R}$ test strength parameters in stability analyses for certain conditions of consolidation and drainage.

91. Figure 33 shows change in standard deviation from the control condition at the end of the test versus pore-pressure response at the end of the test for all cyclically loaded specimens except specimens 18 and 52 through 56. Specimen 18 was not included since it is believed that the high pressure

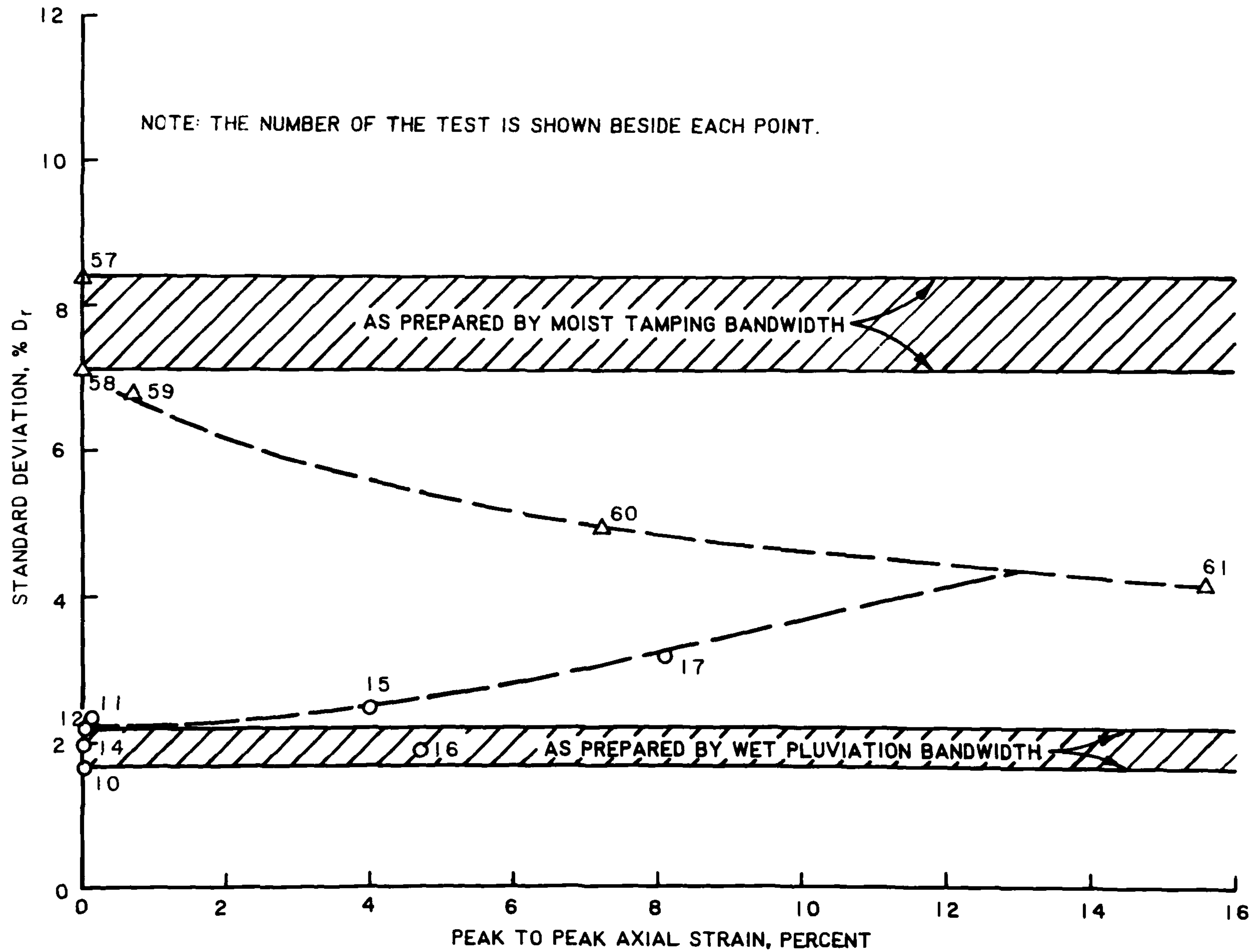

Figure 31. Redistribution in specimens at 60 percent relative density

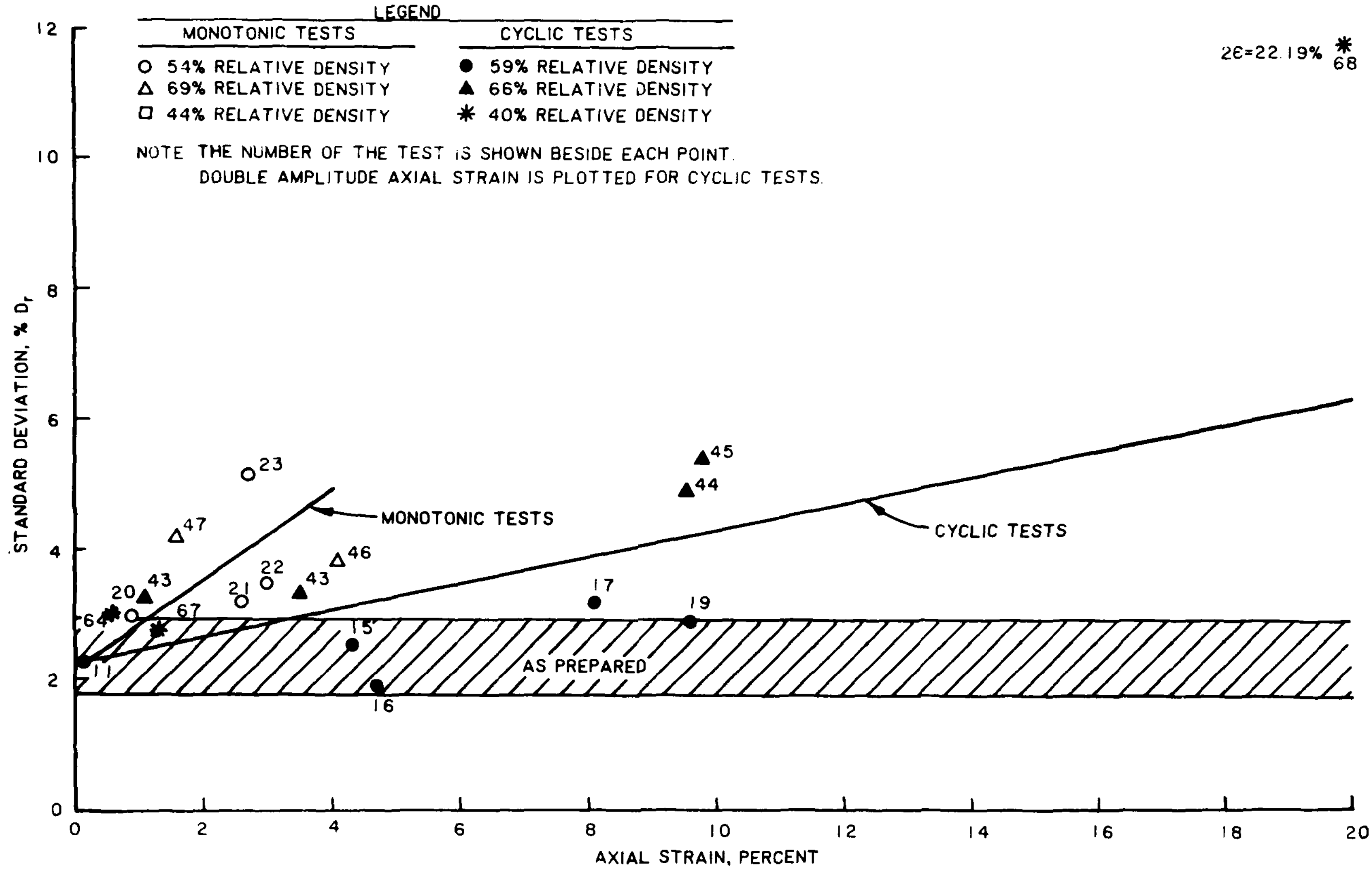

Figure 32. Axial strain versus standard deviation for cyclic and monotonic load tests

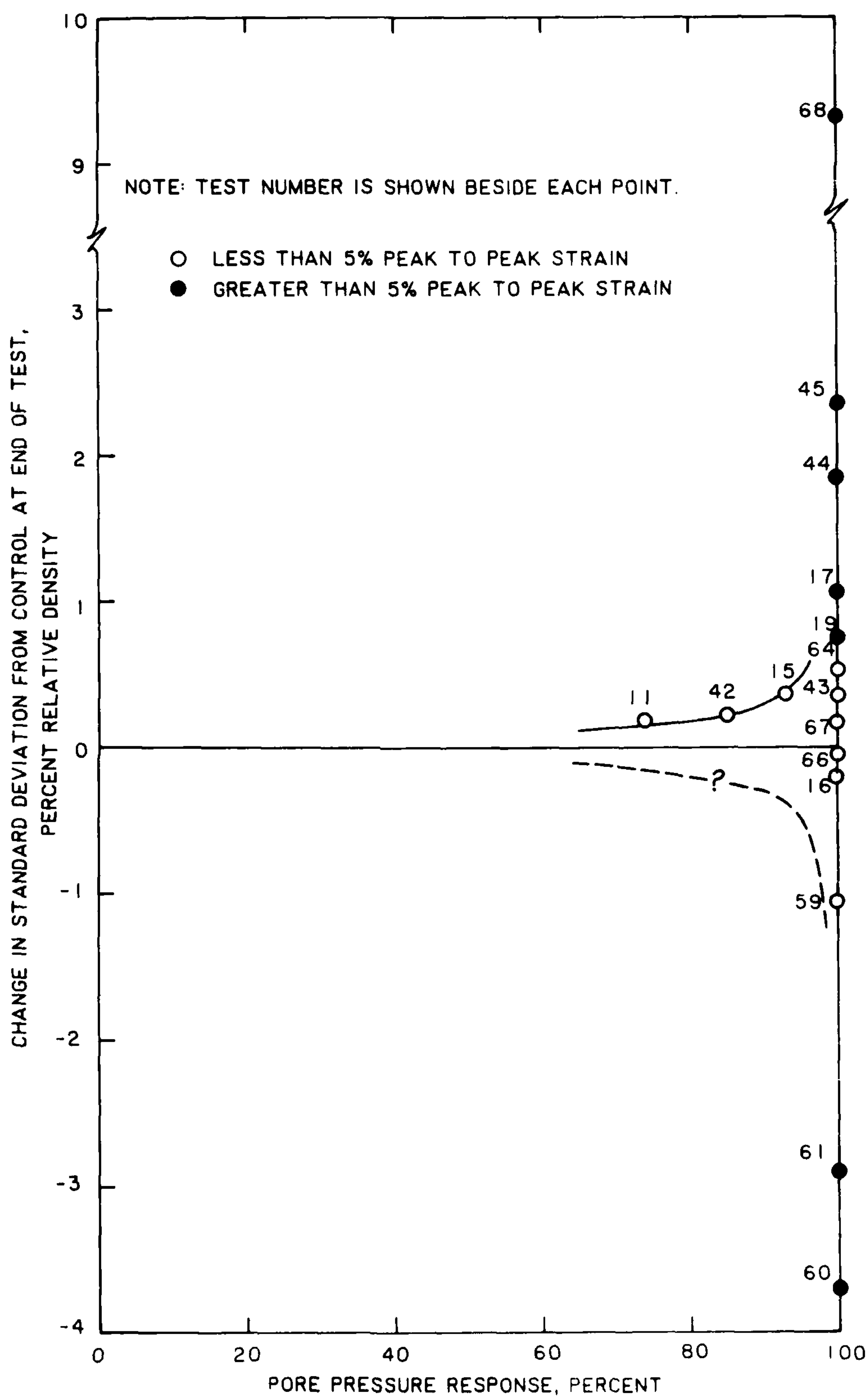

Figure 33. Pore pressure response versus change in standard deviation

under which it was consolidated introduced nonuniformity and therefore increased the standard deviation of this specimen. Specimens 52 through 56 were not included in the figure because they were molded on the erratic vibratory table which rendered their initial condition of density homogeneity uncertain.

92. From Figure 33 it is seen that the standard deviation may increase from 1/2 to 1 percent above the control state as the pore pressure increases to 100 percent response if the peak-to-peak strain remains less than 5 percent. The change in standard deviation may be quite large if there is 100 percent pore-pressure response and the peak-to-peak axial strain is greater than 5 percent. This may be significant since a response of 5 percent peak-to-peak strain in cyclic triaxial specimens is a commonly used analysis and design strain criterion. The unmistakable suggestion of Figure 33 is that redistribution (in terms of increase in standard deviation from the control condition) tends to remain small at double amplitude strain levels up to 5 percent and pore-pressure responses up to about 90 percent. Redistribution increases significantly beyond these strain and pore-pressure conditions, but the amount of redistribution which would render measured material responses invalid in the cyclic triaxial test is unknown and not addressed by this research.

PART V: WORK BY OTHERS AND FUNDAMENTAL CONCEPTS

93. The ideal object of laboratory soil testing is to study the behavior of a given soil under conditions similar to those encountered in situ as well as to obtain parameters which can be used to describe their behavior in terms of constitutive equations. In a laboratory test, the specimen is intended and generally assumed to represent a single point in a soil medium, that is, a differential element. It is assumed to be homogeneous and isotropic. All components of the stress tensor must be measurable or be zero for the true material properties test. The validity of these assumptions depends on the uniformity of the stress and strain distribution as well as the degree of uniformity (homogeneity) and isotropy within the soil specimen. Departure from a uniform stress, strain, and density distribution indicates departure from the fundamental assumptions of a laboratory material property test. It has long been recognized that laboratory test conditions are imperfect and influence, to a greater or lesser extent, constitutive properties measured in a soil specimen. Several investigators have sought to study internal conditions and mechanisms at work in laboratory test specimens in an attempt to evaluate the severity of uncontrollable external influences.

94. Balla (1960) developed expressions for the stress and strain distribution in an elastic solid cylinder subjected to axial and radial pressures with varying degrees of end restraint. This work is a valuable contribution toward the analysis of triaxial test specimens under load. Unfortunately, because it was necessary to make the assumptions of classical elastic theory, the solution is of limited usefulness because soil and earth materials tested in triaxial compression are seldom linearly elastic.

95. In a laboratory study by Shockley and Ahlvin (1960), the behavior of dry and saturated undrained triaxial specimens of sand subjected to axial loading was examined by studying exterior deformation patterns. Strains were back-computed from careful vertical and lateral deformation measurements made on the surface of triaxial specimens under test. Direct measurement of stress was made in a few tests in a large triaxial specimen 35 in. in diameter with implanted pressure cells. Strain was measured in specimens using electronic strain gages. Internal conditions were explored with a technique where specimens were drained after loading, quick frozen, cut top to bottom into four

axially symmetric slices or elements, and the density of each element determined by volumetric methods.

96. That study concluded that a nonuniform pattern of stresses and strains exists within a triaxial test specimen; nonuniform volume changes occur internally.

97. In a study by Castro (1969) to develop laboratory tests which precisely define the critical void ratio line, a limited investigation was conducted to evaluate the development of nonuniformities in triaxial specimens during cyclic loading. Specimens were molded by compacting layers of moist soil into a mold with a rod driven by a constant force. These specimens were loaded to various strain levels and, in some instances, reconsolidated after loading to increase the effective stress to a level where the specimen could be handled. The specimen was then removed from the pressurized triaxial chamber, laid on its side, and covered with a cold (approximately -50° C) solution to freeze it. The excess volume of ice which was expelled during freezing collected along the top ridge of the specimen and was removed. The specimen was then sliced into elements and analyzed for density redistribution. This freezing technique was crude compared to the one used herein and results were considered preliminary, but represented a starting point in the search for a procedure to directly examine internal disturbances in triaxial test specimens.

98. Following the work by Castro, a laboratory study was conducted at Harvard by Casagrande and Rendon (1978) where short circular specimens, 6.8 cm in diameter and 3 cm high, were subjected to cycles of simple (reciprocating) and gyratory shear, after which the specimens were frozen and analyzed for density redistribution. The specimen was confined by a membrane inside a flat coiled spring called a "Slinky." Since the Slinky allowed little lateral movement, consolidation was essentially one dimensional. Specimens were saturated with the application of 1 kg/cm^2 back pressure and frozen with access to drainage against a constant pressure. This operation allowed the expulsion of excess volume associated with the phase change from water to ice, and laid the groundwork for the present investigation. This freezing technique yielded specimens undisturbed by the freezing process and, therefore, the data generated by this investigation may be directly comparable to that of the present study. These results were discussed by Casagrande (1975) and summarized by Casagrande and Rendon (1978).

99. Singh, Seed, and Chan (1979) conducted a laboratory study to

investigate the effects of disturbance due to sampling on cohesionless soil. Part of this study involved the freezing of 12-in.-diam triaxial specimens and the coring, thawing, and cyclic loading of 2.8-in.-diam cylinders from the larger frozen specimen. This study showed that during freezing, if the confining pressure is maintained and the excess volume of water associated with the phase changes is allowed to drain from the specimen freely, then the volume changes during freezing are insignificant and the cyclic strength characteristics are not altered by the freezing and subsequent thawing process. These investigations conclude that the "unidirectional freezing technique" (that is freezing sand samples in sampling tubes after drainage of water from the tube is allowed) offers great promise as a means of stabilizing the structure of a sand against disturbances during handling and transportation. However, if the sampling tube is not allowed to drain and subjected to "all around" freezing, severe disturbance of the saturated sand structure will occur.

PART VI: COMPARISON WITH WORK BY OTHERS

Shockley and Ahlvin

100. The work by Shockley and Ahlvin conclusively demonstrated the occurrence of stress and strain nonuniformities in laboratory triaxial test specimens. Rough end platens were used in the performance of the tests, and the dissection analysis of saturated specimens showed that under constant-volume axial compression, nonuniform density (volume) changes occur throughout the specimen. Analysis of specimens after axial strain showed that the greatest decrease in density (increase in volume) occurred in the middle third of the specimen just below the geometric center, and this region of the specimen was stated to typically contain the visual failure zone or "bulge."

101. Sand specimens were prepared dry at medium dense and loose relative densities and saturated by filling the specimen with ammonia gas and then introducing water from the bottom. By this process, degrees of saturation of 99 percent or greater could be achieved. These specimens were axially loaded at constant volume using either a test procedure where the lateral (chamber) pressure was held constant and the pore pressure controlled, or the pore pressure held constant and the lateral pressure controlled. The figure summarizing the volume changes in the specimens of the Shockley and Ahlvin investigation is reproduced here as Figure 34 and shows density after loading plotted versus height in the test specimen.

102. There is an unmistakable region of lower density in the central zone of these specimens which were loaded to 10 percent axial strain. The figures on the left labeled "consolidated" show the initial condition of density distribution in prepared control specimens. From this figure, it is evident that density change occurs in the specimen as a result of axial loading.

103. Four monotonic load tests were performed on specimens at an average relative density of about 54 percent for the present investigation. Because of the highly dilative response of the material tested in the present study (see Figure 18), specimens could not be deformed to the large strains of the Shockley and Ahlvin study without cavitation, the loss of saturation, and, hence, invalidation of the density analysis. A plot of relative density versus height for four monotonic tests of the present study is shown in Figure 27. These four tests were performed at 54 percent relative density which

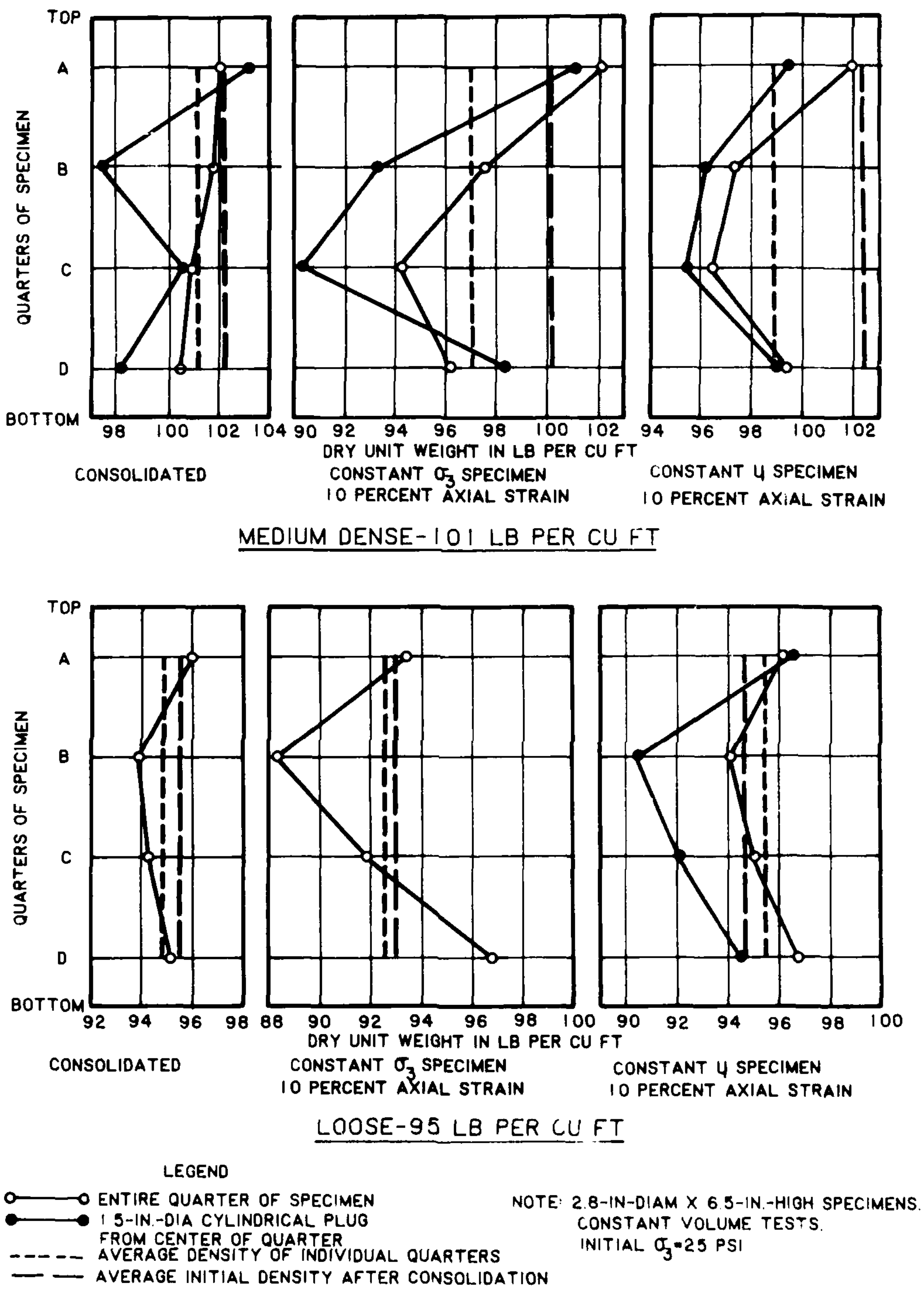

Figure 34. Volume changes in triaxial specimens of saturated fine sand (from Shockley and Ahlvin 1960)

corresponds to about 100 pcf and, therefore, these specimens may be directly comparable to the medium dense specimens of the Shockley and Ahlvin study at 101 pcf. In addition nontilting caps were used in both studies, but the Shockley and Ahlvin membranes were about twice as thick as those of the present study. The patterns of Figure 27 seem almost random with no particular trend ar', as such, show poor agreement with the well defined and consistent patte of the Shockley and Ahlvin work. Several reasons could account for this. First, the Shockley and Ahlvin specimens were loaded to 10 percent axial strain where a visual failure bulge in the center of the specimen could be seen. This more than anything else is believed to account for the pattern differences as specimens in the present study could only be loaded to relatively small strain (3 to 4 percent) to avoid cavitation and the loss of the test. No bulge in the central zone in the specimen of the present study could be seen with the unaided eye, and the specimen appeared to deform as a right circular cylinder. The well defined pattern of the Shockley and Ahlvin specimens may have been due to the relatively large induced axial strain. Next, the Shockley and Ahlvin work was performed before the advent of back-pressure saturation and specimens in this investigation were stated to have a degree of saturation of 99 percent; whereas, specimens of the present study were back-pressure saturated to a Skempton B parameter of 96 percent or greater. Considering this, if there were a tendency for dilation to occur in the Shockley and Ahlvin investigation, then the specimen might have cavitated and become relatively soft and compliant; volume changes would have occurred quite easily in such a specimen. Conversely, because of the high degree of saturation and dilatant behavior in specimens of the present study, particle-to-particle pressure in the test specimen increased as strain occurred, making particle rearrangement and volume change more difficult with increasing axial strain. Without cavitation (which was not allowed to occur), volume change in these specimens would be small. This may be borne out by considering that the specimens of the present study remained quite uniform after loading. In Figure 27, for example, specimen 22 shows the widest dispersion of density change which is seen to be about 7 percent relative density. This corresponds to a dispersion in mass density of less than 1.3 pcf within the layers of that specimen after loading. This is compared to an initial dispersion of 2 pcf in the Shockley and Ahlvin specimens, which became 8 pcf after loading in the specimen tested under constant chamber pressure.

104. It is believed that sufficient axial strain was *not* permitted to occur in specimens of the present study to develop the pattern of the Shockley and Ahlvin specimens. The pattern observed in specimens of the present study is believed to reflect random placement (molding) patterns. This may be borne out by examining the seemingly random pattern of the control specimens shown in Figure 35.

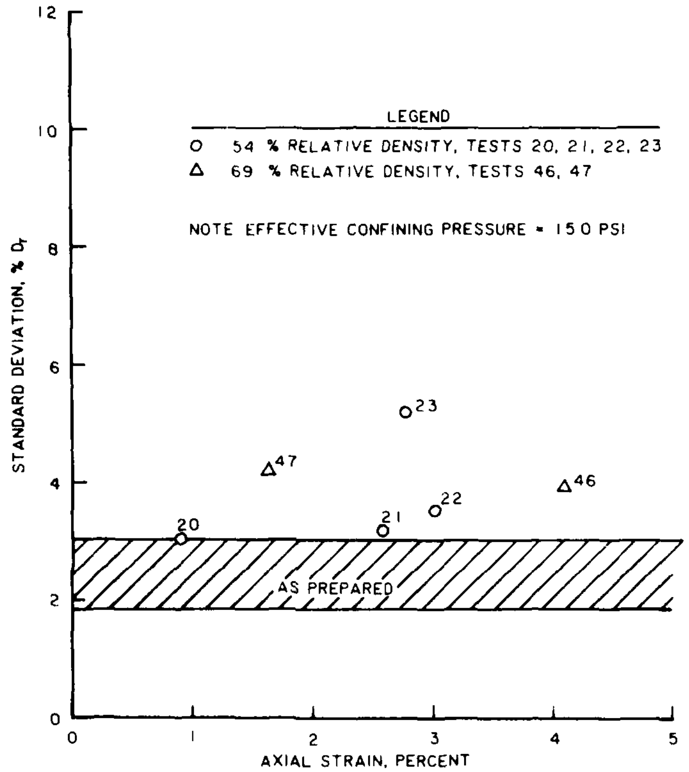

Figure 35. Standard deviation versus axial strain in monotonic load tests

105. Figure 35 is a plot of density dispersion (expressed as standard deviation) versus axial strain in monotonically loaded specimens of the present study. This plot demonstrates that nonuniformity increases if the specimen is axially strained in that density dispersion (standard deviation) is higher in all specimens subjected to axial strain than in the as-prepared or unstrained specimens even though no consistent change in standard deviation pattern could be detected in specimens of the present study. The combined suggestion of the Shockley and Ahlvin's work and the present study then is that nonuniformity begins to increase with the application of axial strain in

triaxial specimens subjected to monotonic loading and continues to increase as axial strain increases.

Castro

106. The laboratory work on redistribution analysis by Castro was, in part, performed on the same type of sand as the present study. However, the method of placement and freezing technique were so different that direct comparison of redistribution analysis may not be possible. The results of two cyclic load tests at a density of about 60 percent relative density were reported by Castro (1969). These are shown in Figure 36 along with the results of a 60 percent relative density specimen from the present study tested under an effective confining pressure of 60 psi, which is close to the confining pressure of 4 kg/cm^2 used by Castro. The WES specimen is observed to be more resistant to cyclic loading, which may represent the difference in placement technique--placement by wet pluviation in the case of the WES specimen and a modified moist-tamping technique for the Castro specimens.

Rendon

107. The laboratory study by Rendon was performed on the same sand as the present study. An extensive procedure for molding uniform specimens was developed and the freezing and analysis techniques were similar to those of the present study. For the purpose of comparison with data generated by this investigation, shear strain versus redistribution (i.e., standard deviation) data were taken from Casagrande and Rendon (1978) and are shown in Table 8. The reader should be aware that the Casagrande/Rendon specimen was dissected into 64 elements, and the WES specimen was dissected into 96. In spite of these differences, these data will be compared directly. The upper and lower limits of the Harvard as-prepared bandwidth are, respectively, 2.8 and 1.9 percent relative density percentage points; whereas, the upper and lower limits of the WES bandwidth are 1.67 and 2.63 relative density percentage points, respectively.

108. The results of cyclic triaxial tests are shown plotted with the results of cyclic simple shear tests in Figure 37. The figure shows standard deviation, a measure of density dispersion, versus percent shear strain. Maximum shear strain in triaxial specimens, γ , is taken as

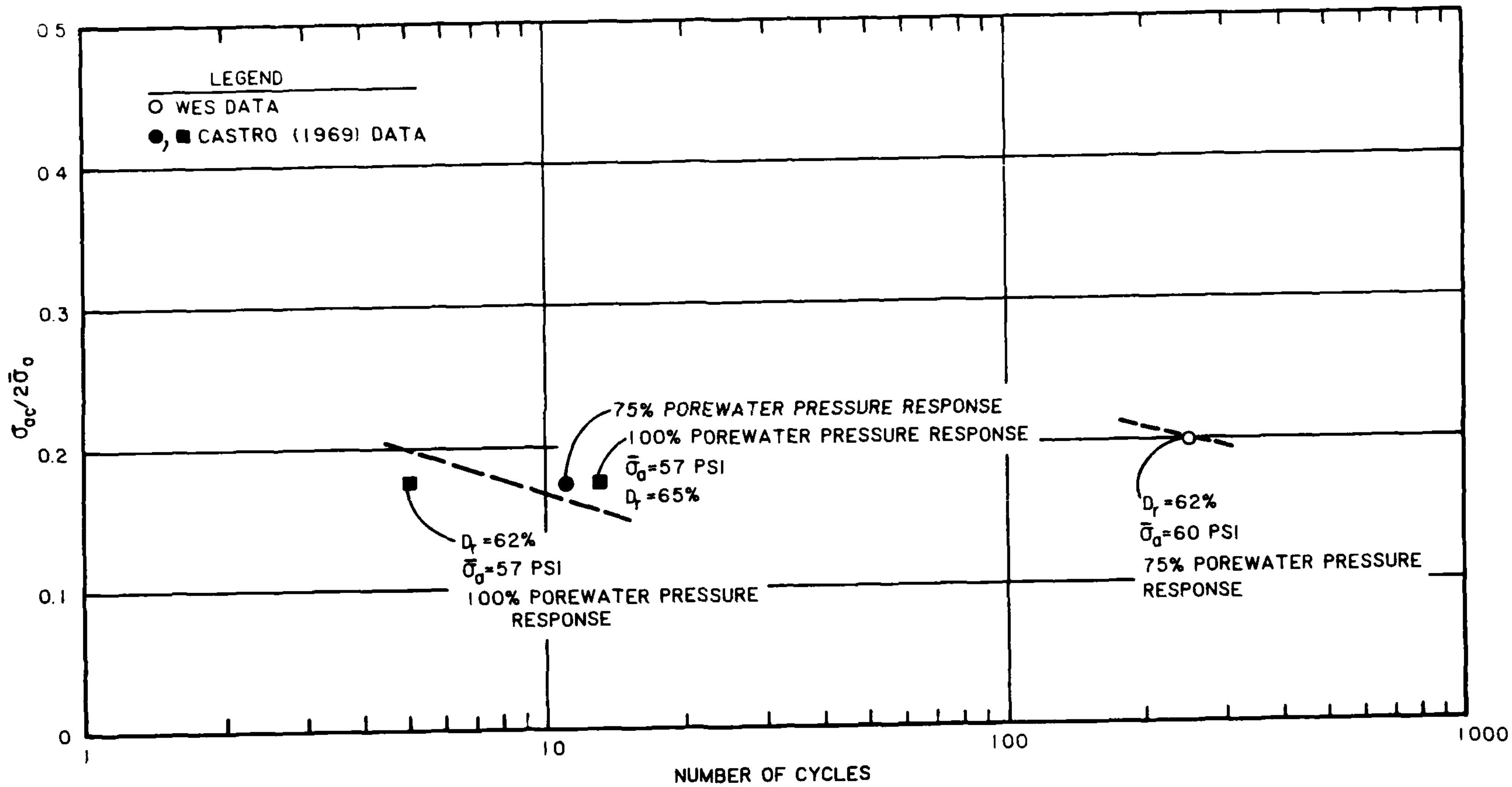

Figure 36. Comparison of Harvard and WES triaxial specimens subjected to cyclic loading

Table 8

Casagrande and Rendon (1978) Reciprocating Shear Test Data

Test No.	Relative Density percent	Number of Cycles Applied	Standard Deviation Percent Relative Density	Shear Strain percent
1	58	24	7.4	35
2	60	25	8.1	34
4	62	64	10.1	30
5	73	71	5.8	22
12	91	100	2.5	8
13	40	7	9.8	45
14	52	10	6.2	37
17	69	25	8.7	27
18	67	100	6.4	25
19	88	200	4.3	12
21	57	10	5.2	29
22	58	25	8.5	39
23	62	100	7.9	33
24	49	12	10.0	45

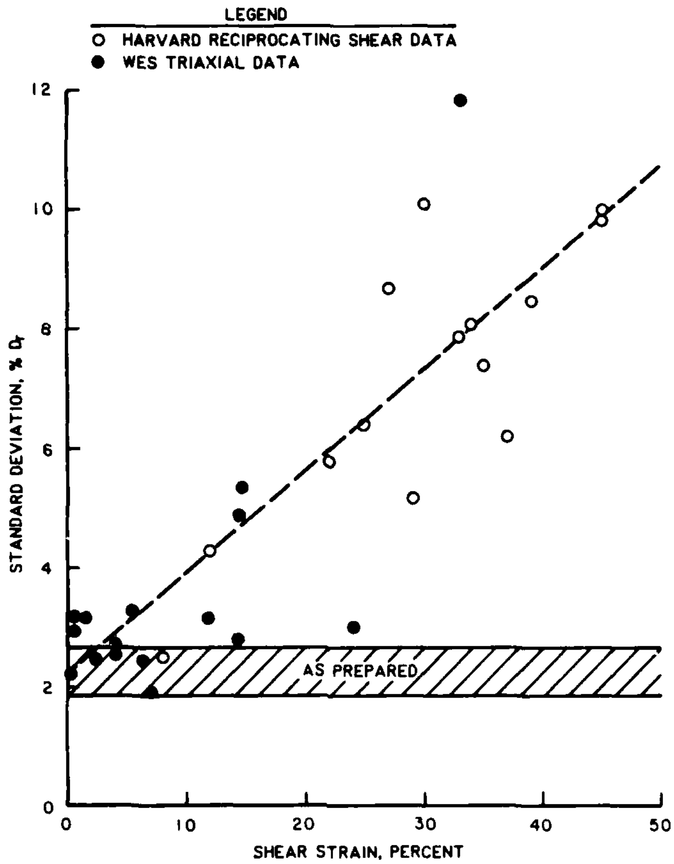

Figure 37. Comparison of Harvard and WES cyclic response data

$$\gamma = \frac{3}{2} \varepsilon_a \qquad (8)$$

where ε_a is the axial strain in triaxial test specimen. This expression follows directly from the assumption of constant volume in the triaxial test specimen. Shear strain in the simple shear test was computed directly from measured shear displacement. The plot shows that shear strain and standard deviation in the Casagrande and Rendon simple shear specimens tended to be higher than those in WES triaxial test specimens.

Singh, Seed, and Chan

109. The laboratory study conducted by Singh, Seed, and Chan (1979) is not directly comparable with the present study except that their investigation convincingly demonstrated that if sand specimens are frozen under pressure but

with access to drainage to allow the excess volume of water due to phase change to escape, then the freezing process will not disturb the granular skeleton of the soil specimen under investigation. The present investigation has confirmed this fact in two ways. First, by knowing the volume of void space within the specimen which is being frozen, the predicted amount of water was always expelled. Second, density uniformity was always within the expected range in the control specimens and no unexpected (and unrealistic) density aberrations appeared in specimens which were loaded and subsequently frozen.

Mulilis, Chan, and Seed

110. Mulilis, Chan, and Seed (1975) performed a study to investigate the effects of method of specimen preparation on the cyclic stress-strain behavior of sands. They found that at 50 percent relative density and an effective confining pressure of 8 psi, moist tamping produced stronger specimens than those produced by pluviation through water.

111. The finding of the present study is that at 60 percent relative density and an effective confining pressure of 15 psi, pluviation through water with indirect impact compaction produced a stronger and more homogeneous specimen than moist tamping. However, the results of the two studies may not be directly comparable because of the very different methods of water pluviation used. The sand specimens of Mulilis, Chan, and Seed were formed by pouring a known weight of sand from a water-filled flask into a water-filled mold, placing a surcharge on top of the sand specimen and vibrating the sides of the mold with a hand-held vibrator until the sand densified to fill the desired volume. The asymmetric vibration of the mold may have produced a very nonuniform and consequently weak specimen. Pluviation through air produced the least homogeneous specimens in the present study. Specimens formed by pluviation through air were not tested for strength in the present study, but since indications are that strength decreases as density homogeneity decreases, it is possible that specimens formed by pluviation through air would be the weakest of all those investigated.

112. Mulilis, Chan, and Seed specimens were 7 in. high and 2.8 in. in diameter. To investigate initial density uniformity, specimens were placed and then a vacuum was used to remove the specimen in four layers for density

determination. Three layers 2 in. thick were removed, followed by the remaining layer 1 in. thick. The material comprising each layer was weighed and the relative density of the layer determined. The indications of the present study are that Mulilis et al.'s measurements were too coarse to identify density patterns or detect small changes in density uniformity. For example, about 27 elements from a specimen of the present study would be averaged in one equivalent element of the Mulilis et al. specimen. Therefore, detection of density nonuniformity which might radically alter the cyclic strength characteristics of sand was not possible with the procedure employed by Mulilis, Chan, and Seed.

113. However, the findings of Mulilis et al. are in general agreement with those of the present study. For example, Mulilis, Chan, and Seed concluded that the dynamic strength of saturated sands formed by different compaction procedures was significantly different. The present study confirms this conclusion.

114. Mulilis, Chan, and Seed found that the dynamic strength of a composite specimen of sand (i.e., a dense sample containing a layer of loose material) is a function of the thickness of the loose layer. The present study also supports this conclusion. For example, the strength of the composite specimen tested in this study was intermediate to the strength of the high and low density layers. It naturally follows that if the thickness of the loose layer becomes very small, the strength of the specimen would approach the strength of the dense portion of the specimen.

115. Mulilis, Chan, and Seed conclude that both fabric and particle orientation were probably the primary reasons for observed differences in the dynamic strength of sand. The results of this study, however, suggest that these differences may be more appropriately explained in terms of density inhomogeneity within the soil specimen. For example, Mulilis et al. found that moist-tamped specimens were stronger than specimens pluviated through air. In the present study, initial average standard deviations in relative density percentage points in moist-tamped specimens and air-pluviated specimens were found to be 7.8 and 8.8, respectively, indicating that moist-tamped specimens are more uniform. Moist-tamped specimens should therefore be stronger. The suggestion of this study is that there is a strong correlation between density uniformity and strength. Mulilis, Chan, and Seed state that "A deposit of sand in the field could exhibit a packing arrangement that is highly resistant

to liquefaction. Upon remolding the soil, the original structure would be destroyed and a new structure formed which could be more susceptible to liquefaction." It is acknowledged that if structure in such a soil existed, it would be damaged or destroyed by remolding. It is believed that with normal remolding procedures, an undisturbed sand specimen could never be replaced at its initial state of density homogeneity and would show a greater tendency toward instability in its remolded state. However, increased density inhomogeneity is believed to be the cause of the decreased stability. Change in fabric is believed to be a coincidence.

PART VII: IMPLICATIONS OF THIS STUDY

Engineering Practice

116. The underlying purpose of this study was to evaluate whether density redistribution, if it occurs, has any significant effect on the results of the cyclic triaxial test and on the application of these results to liquefaction analyses. If a large amount of density redistribution occurs, the strength versus number of cycles relationship determined from a series of cyclic triaxial tests is certainly in question. Undoubtedly, some redistribution of densities must occur in any undrained triaxial test. However, it has been found that all density redistribution occurring before 100 percent pore-pressure response and 5 percent double amplitude strain is reached is so small as to be within the range of initial heterogeneity of control specimens and random in distribution. Therefore, such density redistribution is considered insignificant for practical engineering purposes. However, at 10 percent double amplitude strain this is not the case. By the time the specimen reaches 10 percent double amplitude strain, the effect is clearly significant and well beyond the range of heterogeneity in the control test specimens.

117. The results of this study imply that in isotropically consolidated cyclic triaxial tests at double amplitude strains greater than 5 percent, the effects of density redistribution are serious and the application of such test results to engineering problems is open to serious question. In his lecture at the Fifth Pan-American Conference on Soil Mechanics and Foundation Engineering, at Buenos Aires, Professor A. Casagrande (1975) expressed concern over the occurrence of density redistribution in cyclic triaxial tests and speculated that the effect might be significant at pore-pressure ratios ($\Delta u/\bar{\sigma}_{3c}$) as low as 50 percent. The cyclic triaxial redistribution data available to Professor Casagrande at that time were from rather crude tests conducted by Castro (1969) which were all carried out to strain amplitudes of 10 percent or more. The present results are generally consistent with Castro's test results but indicate that the effects of density redistribution do not become important from a practical point of view at such low pore-pressure ratios or strain amplitudes as Casagrande hypothesized. Casagrande (1975) stated that the radical redistribution of water content (and hence density) was caused by mechanisms not present in the field (instantaneous hydrostatic

state of stress at two points in each cycle for isotropically consolidated specimens and nonuniform boundary conditions) and that this in turn was responsible for the progressive increase in $\Delta u/\bar{\sigma}_{3c}$ and softening of cyclic test specimens.

118. The cyclic triaxial test, like all laboratory soil tests, does not produce a uniform state of stress (or strain) within the test specimen. This probably contributes to the initiation of water content redistribution. Side boundaries are subjected to a uniform radial stress and are free to deform. Top and bottom boundaries (end caps) are subjected to uniform vertical deformation, controlled total vertical load, and uncontrolled frictional forces which resist any tendency toward radial movement at the end caps. Because of nonuniform applied stress, strain within the specimen must be nonuniform and hence pore pressures measured at the ends may not be instantaneously the same as those in the interior of the specimen.

119. The cyclic triaxial test is, strictly speaking, not used in practice as a constitutive property test. No stress-strain relation is derived from it in whole or part. The test has two uses. It is used as an index to compare cyclic strengths of different materials in dams and foundations whose earthquake performance is known and provides a basis for extrapolation to other cases (see Seed, Makdisi, and De Alba 1978). It is also used along with adjustment factors based on empiricism and judgment to establish limiting cyclic shear stresses which are compared to earthquake-induced cyclic shear stresses obtained from one- or two-dimensional stress wave propagation analyses for specified earthquake base motions (Seed 1979). In the former case, a problem exists only if density redistribution becomes so severe that the test is no longer an index of field behavior. From the data given by Seed, Makdisi, and De Alba (1978), apparently this is not the case at 100 percent $\Delta u/\sigma_{3c}$ and/or 5 percent double amplitude strain. Some of the effects of density redistribution would be masked when the test is used as an index, because the effect, whatever it is, is present to roughly the same degree in all tests. In the use of the test results for comparison with wave propagation analysis results to make judgments about earthquake-induced liquefaction and/or deformation, the effects of density redistribution could be more serious and the possibility that stress states not realistic for the field are causing density redistribution and softening must be considered. However, the choice of empirical and judgmental adjustment factors (which range from 0.57 to 0.90 as a

function of σ_{1c}/σ_{3c}) and the choice of 100 percent $\Delta u/\sigma_{3c}$ as measured at the ends of the specimen or 5 percent double amplitude axial strains as analogous to the limit of acceptable field performance also are significant in the second application of the test and are really based on quite limited data. It is possible (although there are no data to support or deny this) that these factors compensate to some degree for any effect of redistribution at 5 percent amplitude strain and below.

120. In this study, there were two rather surprising test results from Tests 11 and 69/70. In the former, a specimen which, based on past experience, was expected to reach 100 percent pore-pressure ratio in less than 30 cycles took several hundred cycles to reach that level of response. However, it is speculated that this test specimen was more homogeneous than any that had ever been subjected to isotropically consolidated cyclic triaxial testing before. In the second highly significant test it was demonstrated that the cyclic strength versus number of cycles relationship of a moderately dense specimen which contains a thin, low-density layer was very close to that of a large specimen similar to the low-density layer. This indicates that the effects of minor geologic details, such as thin layers of low-density cohesionless materials, have a controlling effect on the cyclic strength of laboratory specimens and quite probably have a controlling effect on cyclic strengths of field deposits as well.

121. In nature, it is highly unlikely that one will ever encounter an 8-in.-thick sequence of materials as homogeneous as those prepared by wet pluviation in this study. Visual observation of alluvial deposits indicate cross-bedding and variations in gradation, both of which were not present in this study; and the mode of deposition of alluvial sands, which involves varying water velocities and varying bottom slopes, implies that there will be a substantial variation in in situ density on the micro scale. All of this taken together indicates that if laboratory cyclic triaxial tests are to be used as a basis for liquefaction analyses, it is important that they be representative of in situ conditions and, moreover, the in situ conditions of critical minor geologic details. This requires the testing of the best possible quality "undisturbed" specimens, instead of remolded ones, as well as knowledge of density variation within the deposit, both horizontally and vertically, at a small scale. As evidence of the criticality of the proper selection of test specimens to represent thin, low-density zones, the cyclic strength of

AD-A148 944 INVESTIGATION OF DENSITY VARIATION IN TRIAXIAL TEST SPECIMENS OF COHESION..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS GEOTE.. P A GILBERT 2/3

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MICROCOPY RESOLUTION TEST CHART
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Test 69/70 was about one-half the cyclic strength of the higher density base material. A variation of 2 in cyclic strength would clearly lead one to vastly different conclusions in any practical liquefaction analysis.

122. At present, there are only two tools available to the geotechnical engineer with which he can find density variations over scales of inches in the vertical direction. These tools are radiography of undisturbed samples in the sample tube and the tip resistance from an electric cone penetrometer. There are no practical tools which will allow such small and detailed variations in the lateral direction to be found, as it is beyond the realm of practicability to obtain undisturbed samples or conduct cone penetration tests at such close spacings. It is believed that if laboratory cyclic triaxial tests are to be used in liquefaction analyses, it is vitally important that the tests be on the best quality "undisturbed" specimens and that the utmost care be taken in selecting specimens to represent the lowest density known to exist in the soil profile. This will require an intensive field investigation to evaluate minor geologic details.

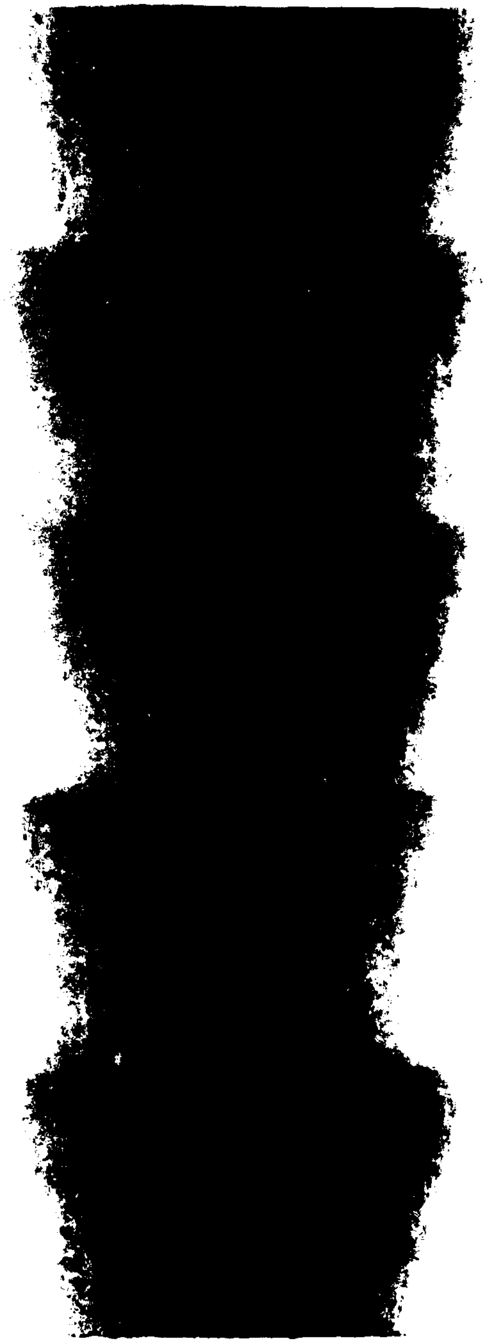
123. The effects of a low-density layer on undrained cyclic triaxial test results lead one to speculate as to what might be the effect of a low-density layer on standard penetration test (SPT) N-values. While no data were obtained in this investigation which would give any insight, common sense and experience suggest that a 1-in.-thick layer of low-density material would not significantly affect the N-value. It is common practice to evaluate liquefaction potential based on N-values. To date, this procedure has been validated for only level ground conditions, but it is routinely used to evaluate the liquefaction potential of dams and foundations. This study suggests that low-density layers are critical to the strengths of the deposit if a static failure mechanism exists--e.g., a driving force. Consequently, the use of the SPT N-values in evaluating nonhomogeneous material under sloping ground conditions is certainly open to question and its use may lead to results that are unconservative.

124. In summary, this study did not invalidate the use of isotropically consolidated cyclic triaxial tests at double amplitude strain levels of 5 percent or less and it shows that in the application of such tests to engineering practice, it is vitally important that the tests be conducted on carefully chosen undisturbed samples.

Past Research

125. In this study, both the cyclic strengths and induced heterogeneities that occurred as a result of changing specimen preparation methods were examined. It was found that cyclic strength in the isotropically consolidated triaxial tests changed by a factor of 2 when the preparation method was changed from a very homogeneous pluviation through water procedure to the commonly used moist-tamping method, with the latter producing lower strength. A similar effect was noted by Mulilis, Chan, and Seed (1975); however, they attributed the strength difference to be different soil fabrics and observed that the relative particle orientations were different in the specimens prepared by moist tamping and pluviation. They did not measure heterogeneity in any meaningful way. In the present study, heterogeneity was measured, and measured carefully. Regrettably, no attempt was made to measure the same index of fabric that Mulilis, Chan, and Seed adopted. The present study presents strong evidence that the greater the heterogeneity of the specimen, the lower the cyclic strength; and it provides an alternative explanation to the effect that Mulilis, Chan, and Seed ascribed to soil fabric.

126. It is possible that the effects of different placement procedures on the cyclic strength of remolded specimens are entirely due to heterogeneity and that Mulilis, Chan, and Seed's fabric observation was coincidental, or it is possible that the observed trend is a combination of both effects. Certainly, what Mulilis et al. ascribed to fabric was not due to fabric alone. Figure 38 is a radiograph of a moist-tamped specimen prepared by Mulilis while he was employed at WES and shows definite vertical density gradients, with the top of each layer being denser than the bottom. This figure is direct evidence of heterogeneity within Mulilis, Chan, and Seed's specimens. Regrettably, like radiographs of the low-heterogeneity specimens prepared in this study by wet pluviation do not exist. However, the data do not indicate any systematic vertical trends in density such as can be seen in the figure, and the extent of the density variation in the control specimens is not likely to show up in the radiograph given the procedures that were used to prepare the photo in Figure 38. This leads one to speculate that contradictions in past studies on the relation between resistance to cyclic load and density, or indications that factors other than density may control the cyclic strength, might be greatly reduced or eliminated if the cyclic strengths could be related to



X-RADIOGRAPH OF A LABORATORY
SPECIMEN CONSTITUTED IN LAYERS
TO A DRY DENSITY OF 1.79 g cm^3

Figure 38. X-radiograph of moist-tamped specimen prepared by Mulilis to a dry density of 1.79 g/cm^3

strengths could be related to the minimum density in the specimen rather than the average density.

127. In summary, a new significant independent variable that affects the cyclic triaxial test has been discovered. That variable is the degree of heterogeneity. While almost all past researchers attempted to produce reasonably homogeneous specimens, it is obvious, based on the degree of difficulty that was encountered in getting a fairly homogeneous specimen in this study, that most of them certainly failed. They did not know that they had failed because they did not adopt a spatial density measurement scheme at all or did not adopt one that was as precise as that used in this investigation. The failure to control an independent variable which may have an effect as large as a factor of 2 on the cyclic strength at a given number of cycles, opens to question many of the cyclic triaxial tests parametric studies that have been conducted in the past. However, in those cases where a high degree of repeatability in the "pivot point" test was demonstrated by the investigator, it is likely that although the degree of heterogeneity was unmeasured, its variation was kept within reasonable limits in the test program. The effects of heterogeneity variation shown in this study for isotropically consolidated cyclic triaxial test specimens raised the question of whether or not similar effects would occur in an isotropically consolidated cyclic triaxial test specimen or in cyclic triaxial tests on overconsolidated specimens. Limited tests to evaluate this question and to obtain radiographs of specimens prepared by the wet pluviation method used in this study appear worthwhile.

PART VIII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

128. Based on the tests conducted and comparison of the results with the work of other investigators, the following conclusions are believed warranted:

- a. The data obtained demonstrated most clearly that a highly repeatable average density (from specimen to specimen) is not an indication of a high degree of specimen uniformity. During an investigation early in this study utilizing specimen placement by pluviation through air, it was determined that specimens of a nominal 3,000-g mass in a volume of 1,850 cm^3 could be reproduced within ±4 g. When these specimens were analyzed for density uniformity, it was determined that they were the most nonuniform observed in this investigation.
- b. Uniform specimens are stronger and more stable under cyclic loading than nonuniform specimens. This conclusion is supported by a direct comparison of the load response of very uniform specimens obtained by pluviation through water with less uniform specimens obtained by the technique of moist tamping. Monotonic load tests on moist-tamped specimens were not performed, but comparison of tests performed on uniform specimens of about 54 percent relative density with less uniform specimens at 69 percent relative density shows that the more uniform specimens develop higher axial loads and higher negative pore-water pressure at the same strain level than less uniform specimens. This would indicate that in monotonic loading, uniform specimens are more dilative than less uniform specimens.
- c. Density redistribution as a result of cyclic and monotonic loading does occur and appears to increase with strain level. This is convincingly demonstrated by considering the change in specimen uniformity expressed as standard deviation from the as-prepared state to the after-loading state for both initially uniform and nonuniform specimens. In initially uniform specimens with low as-prepared standard deviations, the standard deviation appears to increase with axial strain (in both cyclic and monotonic tests). In initially nonuniform specimens (moist tamped to 60 percent relative density) with relatively high as-placed standard deviations, the standard deviation appears to decrease with increasing axial strains under cyclic loading. In the composite specimen composed of a uniform layer at a lower density inside an otherwise uniform specimen of a higher density, density in the layer of low relative density increased, while density in the layers of high relative density decreased as a result of cyclic loading.

129. All these observations suggest the occurrence of density redistribution as a result of cyclic and/or monotonic loading. It has been demonstrated also that density redistribution increases with pore-pressure response.

Redistribution measured in terms of change in standard deviation may increase by no more than 1 percent relative density from the control condition at pore-pressure response up to 100 percent if peak-to-peak axial strain remains less than 5 percent. Above 5 percent peak-to-peak axial strain, however, there appear to be large increases in standard deviation and hence large increases in density redistribution.

Recommendations

130. Based on the results of a literature search and the results of this investigation, the following recommendations may be made:

a. This study and other similar investigations described in the literature suggest that, if properly applied, the technique of soil freezing may be used to preserve the structure and integrity of cohesionless soils, permitting truly undisturbed samples of cohesionless soil to be taken. Such samples could be examined and studied in environmental rooms such as the one described in this investigation to determine soil properties which could not be determined before the inception of such techniques. For example, the uniformity of in situ cohesionless soil has never been investigated. Freezing techniques may be used to recover truly undisturbed in situ specimens of cohesionless soil and a procedure similar to that described herein may be used to determine the state of in situ density uniformity. It has been shown in this study that the indicated strength and stability of cohesionless soil in cyclic triaxial compression are highly dependent on the initial state of density uniformity. This would tend to suggest that density uniformity may be as important a variable in the evaluation of stress-strain and strength behavior of cohesionless soil as density, and to date, little has been done in the quantitative evaluation of density uniformity in cohesionless soil.

b. Work similar to that of this study should be performed to evaluate the effect of an isotropic consolidation and also the effect of overconsolidation on density redistribution. A systematic radiographic study of the control and shear specimens should be performed in any subsequent investigation to determine whether the initial state of density uniformity may be more precisely established before cyclic loading.

c. As a result of this study, it is recommended that the use of cyclic strength versus number of strain cycles for double amplitude strain levels of 10 percent not be used in any future analysis of practical earthquake engineering problems.

d. As called for by Casagrande (1975) and Castro (1969), the search should continue for a dynamic laboratory test which will produce in laboratory specimens the uniform stress condition that exists during cyclic loading in situ. However, efforts should also continue to obtain data from actual seismic events so that correlation may be established between laboratory tests and the full-scale tests performed in nature during earthquakes.

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APPENDIX A

COMPUTER CODE

1. The computer code listed below was used for the analysis of density distribution in this investigation. The code was used at WES on a Honeywell 635 computer in the time-sharing mode. The code computes an array of ice contents from two files; one is the array of tare weights that is stored permanently in the computer and the other is wet and dry weights of soil read in for each specimen analyzed. From ice contents, relative densities are determined and printed along with certain statistical parameters.

2. The code will request the name of the file of wet and dry soil weights and will check to see that the number of entries in that file is correct and consistent. The code has the capability of computing correct statistical parameters for a variable number of slabs and elements within slabs. However, the standard number of slabs is 8, with 12 elements within a slab. If other than this standard arrangement is required, then the variables IDE and LGH must be changed accordingly in the main body of the code:

IDE = number of slabs required

LGH = number of elements within a slab

3. Tare weights and wet and dry soil weights are coordinated by line number in the data files. Care must be taken to assign line numbers of the wet and dry weights identical to the tare number containing that soil element. Otherwise, an incorrect tare weight will be selected and an incorrect density will be computed. It is, however, very unlikely that this sort of mismatch could occur.

```
*#RUN FREEZE
C        07.02.06 09:24:32  FREEZE PROGRAM
C
C                THIS PROGRAM IS USED TO COMPUTE A RECTANGULAR MATRIX OF
C           ICE CONTENTS AND RELATIVES DENSITIES WITH STATISTICAL PARAMETERS.
C
C    - SPECIFICATION STATEMENTS -
            DIMENSION WT(108), WWT(108), DWT(108), W(108), DW(108),
     &         WDW(108), X(108), Z(9), ZL(9), C(12), CL(12), CIS(9),
     &         CIC(12), RD(108)
      CHARACTER FNA*4(4)/"    /", "####", "####", ";    "/,
     &    SLB(9)/"  ", "  ", "S", "L", "A", "B", "  ", "  ", "  "/,
     &    RMN(9)/"I","II","III", "IV","V","VI", "VII","VIII","IX"/
C
      CALL FPARAM(1,132)
C
C    - SET INITIAL VALUES -
            A = 0.0
            B = 0.0
            CE = 0.0
            COUNT = 0.0
            CONT = 0.0
            D = 0.0
            G = 277.4767313
            GG = 992.1284674
            IDE = 12
            LGH = 8
            MXN = IDE * LGH
C    - ATTACH FILE "20" / INPUT TARE WEIGHTS -
            CALL ATTACH(20, "/20;", 3, 0, JST, )
            READ(20, 116) (LNE, WT(K),K=1,108)
C    - ATTACH DATA FILE FOR THIS RUN -
  104       PRINT,"NAME OF DATA FILE"
               READ 108,FNA(2),FNA(3)
  108          FORMAT(2A4)
               CALL ATTACH(34, FNA, 3, 0, KST, )
               KST = FLD(6, 6, KST)
            IF(KST.EQ.0 .OR. KST.EQ.31) GO TO 112
               PRINT, "DATA FILE ATTACHMENT ERR.."
               PRINT, "TRY AGAIN"
            GO TO 104
  112       CONTINUE
```

```
C
C    - DATA INPUT / BEGINING OF CALULATIONS -
      LNE = 1
      DO 136 I=1,MXN
         READ (34, 116, END=140) NTR, WWT(I), DWT(I)
  116    FORMAT( V )
         IF(LNE .EQ. NTR) GO TO 132
            PRINT 120, LNE
  120       FORMAT("LINE # ", I3)
            IF(NTR-LNE .GT. 1) PRINT 124, NTR-1
  124       FORMAT("& TO LINE # ", I3)
            PRINT 128
  128       FORMAT( "& IS MISSING" )
  132    CONTINUE
         LNE = NTR + 1
         W(I) = (WWT(I)-DWT(I)) / (DWT(I)-WT(NTR))
         RD(I) = G - GG*W(I)
         DW(I) = DWT(I) - WT(NTR)
         WDW(I) = DW(I) * W(I)
         A = W(I) + A
         B = DW(I) + B
         CE = WDW(I) + CE
  136 CONTINUE
C    - FULL ARRAY WAS READ IN -
      GO TO 144
  140 CONTINUE
C    - END OF FILE BEFORE ARRAY IS FULL -
         MXN = I - 1
         LGH = MXN / IDE
         IF(LGH*IDE .NE. MXN) STOP "ARRAY IS NOT RECTANGULAR"
      WBAR = G - GG*A/MXN
```

```
      WBAR = G - GG*A/MXN
      A3 = 0.0
      A4 = 0.0
      DO 148 I=1,MXN
         RDW = RD(I) - WBAR
         X(I) = RDW**2
         A3 = A3 + RDW**3
         A4 = A4 + RDW**4
         D = X(I) + D
  148 CONTINUE
      SIGMA = SQRT(D/MXN)
      A3 = (A3/MXN) / SIGMA**3
      A4 = (A4/MXN) / SIGMA**4
      AL = WBAR + SIGMA
      BE = WBAR - SIGMA
      GA = WBAR + 2*SIGMA
      DE = WBAR - 2*SIGMA
      DO 152 I=1,MXN
         IF(RD(I).LT.AL .AND. RD(I).GT.BE) COUNT = COUNT + 1
         IF(RD(I).LT.GA .AND. RD(I).GT.DE) CONT = CONT + 1
  152 CONTINUE
      XCOUNT = COUNT/MXN
      XCONT = CONT/MXN
      GWC = 1.08936*CE/B
      WB82 = G - GG*CE/B
C   - TALLY ACROSS "RD" ARRAY -
         DO 164 J=1,LGH
            TLY = 0.0
            LAS = J*IDE
            IST = LAS+1-IDE
            DO 156 K=IST,LAS
               TLY = TLY+RD(K)
  156       CONTINUE
            S(J) = TLY/IDE
            TLY = 0.0
            DO 160 K=IST,LAS
               TLY = TLY+(RD(K)-S(J))**2
  160       CONTINUE
            SL(J) = SQRT(TLY/IDE)
  164    CONTINUE
C   - TALLY DOWN "RD" ARRAY -
         DO 176 J=1,IDE
            TLY = 0.0
            DO 168 K=J,MXN,IDE
               TLY = TLY+RD(K)
  168       CONTINUE
            C(J) = TLY/LGH
            TLY = 0.0
            DO 172 K=J,MXN,IDE
               TLY = TLY + (RD(K)-C(J))**2
  172       CONTINUE
            CL(J) = SQRT(TLY/LGH)
  176    CONTINUE
```

```
C
C   - OUTPUT -
          PRINT 208,  (J,J=1,IDE)
          KS = 0
          IF(LGH .LE. 7) KS = 1
          IF(IDE .EQ. 4) KS = 2
          IF(IDE .LT. 4) KS = 6
          LAS = 0
          DO 204 J=1,LGH
             IST = LAS+1
             LAS = IST+IDE-1
             KS = KS+1
             PRINT 212, SLB(KS), PMN(J),  (PD(K),K=IST,LAS)
             PRINT 216, RMN(J)
  204     CONTINUE
          PRINT, "BOTTOM"
          PRINT 220,  (J,J=1,IDE)
          PRINT 224,  (C(K),K=1,IDE)
          PRINT 228,  (J,J=1,IDE)
          PRINT 224,  (CL(K),K=1,IDE)
          PRINT 232,  (RMN(K),K=1,LGH)
          PRINT 224,  (S(K),K=1,LGH)
          PRINT 236,  (RMN(K),K=1,LGH)
          PRINT 224,  (SL(K),K=1,LGH)
          PRINT 240, SIGMA, XCOUNT*100.0, XCONT*100.0,
     &       GWC*100.0, WBS2, A3, A4, RMN(LGH), IDE
          PRINT 244
C
C   - OUTPUT FORMATS -
  208 FORMAT(1H /40X///31X,"ANALYSIS OF RELATIVE DENSITY REDISTRI",
     &    "BUTION"//51X,"COLUMN"/"   TOP"/I13,11I8)
  212 FORMAT(1H ,A2,A4,12F8.2)
  216 FORMAT(2H& ,A4)
  220 FORMAT(/20X,"- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -"/
     &    I13,11I8)
  224 FORMAT(/7X,12F8.2)
  228 FORMAT(//20X,"- - STANDARD DEVIATION WITHIN EACH",
     &    " COLUMN - -"/I13,11I8)
  232 FORMAT(//20X,"- - AVERAGE RELATIVE DENSITY FOR EACH",
     &    " SLAB - -"/12X,9A8)
  236 FORMAT(//20X,"- - STANDARD DEVIATION WITHIN EACH SLAB - -"
     &    /12X,9A8)
  240 FORMAT(/10X,"GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY =",
     &    F6.2//10X,"PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION =",
     &    F6.2//10X,"PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION =",
     &    F6.2//10X,"AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN ",
     &    "AFTER TEST =",F6.2//10X,"AVERAGE RELATIVE DENSITY OF ENTIRE ",
     &    "SPECIMEN AFTER TEST =",F6.2//10X,"MOMENT COEFFICIENT OF ",
     &    "SKEWNESS, A3 =",F6.2//10X,"MOMENT COEFFICIENT OF KURTOSIS ",
     &    "A4 =",F6.2//"NOTE 1: UNITS ARE PERCENT RELATIVE DENSITY"/
     &    "NOTE 2: SPECIMEN WAS CUT INTO SLABS",
     &    " LABELED I, II, ... ",A4,"          AND EACH SLAB CUT ",
     &    "INTO SEGMENTS LABELED 1, 2, ... ",I2)
  244 FORMAT(1H1,40X)
      STOP
      END
```

APPENDIX B

COMPUTER ANALYSIS OF DENSITY DISTRIBUTION IN INDIVIDUAL TEST SPECIMENS

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	57.64	55.23	57.11	57.24	55.71	58.13	55.88	56.09	58.57	58.49	58.19	58.05	I
II	57.90	57.19	56.97	56.67	56.92	57.25	56.83	56.09	60.62	58.53	58.48	60.35	II
S III	56.41	57.34	58.36	58.84	56.34	55.27	57.10	54.71	57.91	57.91	57.64	58.76	III
L IV	59.09	61.00	58.24	58.69	57.63	60.42	56.98	56.76	59.80	60.33	60.24	59.09	IV
A V	60.88	59.47	59.73	58.26	57.72	57.80	55.49	56.89	59.49	59.93	61.91	61.34	V
B VI	58.49	59.89	59.52	58.96	59.63	57.95	57.28	57.50	59.73	59.39	59.78	60.97	VI
VII	57.15	59.11	55.43	56.09	54.57	54.85	55.92	55.88	58.93	58.52	56.72	59.73	VII
VIII	57.98	55.70	57.41	58.36	55.18	54.81	56.39	56.24	57.65	58.35	58.71	57.29	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
58.19	58.12	57.85	57.89	56.71	57.06	56.48	56.27	59.09	58.95	58.96	59.45

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.27	1.93	1.33	1.01	1.52	1.84	0.62	0.77	0.95	0.79	1.53	1.32

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
57.20	57.82	57.22	59.02	59.08	59.09	56.91	57.01

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.14	1.38	1.26	1.34	1.82	1.05	1.49	1.26

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 1.67

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 62.50

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.09

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 58.04

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.07

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.40

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B1. Analysis of density distribution, Test 10

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	60.61	59.82	59.16	58.38	61.68	61.30	61.23	61.01	59.51	60.23	57.55	56.41	I
II	54.73	56.76	58.47	58.77	59.34	58.68	58.74	59.38	58.61	57.57	59.07	59.00	II
S III	58.60	57.50	55.89	55.02	55.16	56.72	58.33	56.80	56.64	57.48	55.25	54.18	III
L IV	57.71	57.02	55.19	55.35	55.97	56.62	57.73	57.03	56.35	56.68	56.21	56.07	IV
A V	55.75	54.55	54.14	54.36	55.91	55.71	55.60	56.18	52.62	53.46	55.84	54.20	V
B VI	58.53	56.40	55.03	54.85	57.98	58.24	59.02	57.43	53.93	56.29	55.79	54.84	VI
VII	56.26	56.17	54.76	53.56	56.65	58.01	57.67	56.28	52.18	53.43	54.46	53.89	VII
VIII	55.80	56.70	54.56	55.42	52.78	54.82	53.81	51.12	53.30	53.20	51.29	51.98	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
57.25	56.87	55.90	55.71	56.94	57.51	57.77	56.90	55.39	56.04	55.68	55.07

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.82	1.38	1.76	1.74	2.55	1.88	2.10	2.68	2.61	2.35	2.13	1.96

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
59.74	58.26	56.47	56.49	54.86	56.53	55.28	53.73

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.56	1.28	1.33	0.77	1.09	1.62	1.75	1.71

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.28

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 68.75

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 93.75

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.28

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 56.36

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.06

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.68

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B2. Analysis of density distribution, Test 11

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

SLAB	1	2	3	4	5	6	7	8	9	10	11	12	
top													
I	58.53	57.93	61.27	62.25	62.22	58.53	58.53	58.20	60.35	59.21	59.98	59.61	I
II	60.17	60.76	60.94	60.50	61.03	59.96	60.63	60.51	60.41	59.14	63.26	60.67	II
III	56.84	58.84	60.68	60.96	59.83	58.11	58.16	58.67	60.34	58.28	60.94	58.19	III
IV	61.73	61.74	64.46	65.48	59.88	58.62	58.73	61.48	66.09	63.90	65.30	64.83	IV
V	60.27	60.53	63.76	62.40	57.35	57.31	56.86	58.28	62.94	61.97	61.55	60.77	V
VI	59.06	60.01	62.27	62.22	62.22	58.54	58.50	59.62	60.95	60.20	60.75	60.93	VI
VII	60.19	61.04	62.21	60.43	60.67	61.15	60.71	61.92	60.41	62.56	64.22	62.43	VII
VIII	56.91	57.57	61.70	58.57	56.31	57.28	55.68	56.63	58.53	58.06	57.50	56.56	VIII
bottom													

COLUMN

– – AVERAGE RELATIVE DENSITY OF EACH COLUMN – –

1	2	3	4	5	6	7	8	9	10	11	12
59.21	59.80	62.16	61.60	59.94	58.69	58.47	59.41	61.25	60.42	61.73	60.50

– – STANDARD DEVIATION WITHIN EACH COLUMN – –

1	2	3	4	5	6	7	8	9	10	11	12
1.61	1.42	1.25	1.89	2.00	1.22	1.59	1.69	2.15	2.01	2.39	2.56

– – AVERAGE RELATIVE DENSITY FOR EACH SLAB – –

I	II	III	IV	V	VI	VII	VIII
59.72	60.71	59.14	62.69	60.33	60.44	61.56	57.61

– – STANDARD DEVIATION WITHIN EACH SLAB – –

I	II	III	IV	V	VI	VII	VIII
1.46	1.02	1.28	2.56	2.26	1.31	1.15	[illegible]

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY 2.18

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION 73.44

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST 23.85

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST 60.25

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.33

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.90

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B3. Analysis of density distribution, Test 12

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	56.34	57.02	58.48	58.37	57.46	55.45	54.05	55.83	56.76	54.49	56.86	56.01	I
II	59.36	59.65	60.82	60.93	60.20	59.10	57.23	60.47	59.96	61.10	59.28	59.20	II
S III	60.02	59.59	60.05	61.00	59.73	59.92	60.32	60.40	59.74	60.39	59.90	61.05	III
L IV	60.11	58.82	60.14	61.46	58.37	60.14	60.58	59.57	60.69	58.69	58.99	60.17	IV
A V	56.28	55.92	59.31	60.81	58.96	58.78	57.87	58.58	58.09	57.94	58.57	58.34	V
B VI	54.84	54.27	57.92	59.60	56.76	56.91	57.06	56.29	57.00	56.16	56.37	56.16	VI
VII	58.19	53.87	57.05	54.08	55.71	54.34	55.83	56.14	55.90	55.46	55.54	55.27	VII
VIII	59.04	59.16	61.51	60.60	58.80	60.13	57.53	58.54	60.64	60.17	58.35	57.20	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
58.02	57.29	59.41	59.61	58.25	58.10	57.56	58.23	58.60	58.05	57.98	57.92

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.84	2.22	1.41	2.28	1.42	2.11	2.01	1.79	1.77	2.31	1.44	1.97

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
56.43	59.78	60.18	59.81	58.29	56.61	55.61	59.31

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.31	1.02	0.45	0.89	1.23	1.30	1.16	1.26

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.01

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 62.50

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.07

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 58.23

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.41

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.10

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B4. Analysis of density distribution, Test 14

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	57.76	55.59	59.17	55.32	57.10	56.62	55.76	56.05	57.16	58.29	57.55	58.38	I
II	60.52	61.52	63.30	63.18	61.11	63.78	58.81	60.57	61.36	63.12	62.21	60.56	II
S III	61.53	60.88	65.17	63.61	62.34	62.21	62.30	61.97	63.55	61.90	61.88	62.58	III
L IV	65.92	65.14	65.74	65.56	62.60	62.65	62.54	61.58	61.25	64.76	65.92	63.66	IV
A V	65.31	63.99	64.51	64.35	61.10	61.24	62.02	61.32	63.92	65.25	65.19	63.41	V
B VI	64.81	63.19	64.33	64.07	62.88	61.96	62.87	62.23	62.84	63.74	65.13	65.04	VI
VII	63.33	61.77	62.44	62.81	61.87	61.98	61.91	61.64	60.79	63.88	63.46	61.08	VII
VIII	62.22	60.07	60.77	61.05	59.61	59.53	58.92	57.89	59.53	60.78	61.32	61.11	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
62.67	61.52	63.18	62.49	61.08	61.25	60.64	60.41	61.30	62.71	62.83	61.98

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.57	2.73	2.12	2.97	1.80	2.08	2.37	2.09	2.09	2.16	2.55	1.97

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
57.06	61.67	62.49	63.94	63.47	63.59	62.25	60.23

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.17	1.42	1.09	1.68	1.56	1.04	0.92	1.15

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY - 2.48

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 67.71

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST 23.6[illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 62.0[illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.68

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.11

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B5. Analysis of density distribution, Test 15

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	54.63	54.09	53.51	52.53	53.03	53.22	54.25	[illegible]	[illegible]	[illegible]	[illegible]	54.00	I
II	57.37	57.69	56.61	56.07	56.03	58.40	54.10	55.62	56.91	57.41	56.96	56.26	II
S III	59.63	57.03	55.64	55.21	54.38	54.51	55.28	54.27	56.92	57.74	57.86	56.49	III
L IV	60.37	58.08	57.37	58.00	55.55	55.20	54.99	54.70	57.41	57.44	59.85	57.18	IV
A V	60.53	57.71	56.62	58.22	56.07	55.30	56.14	55.46	58.28	58.26	60.40	57.75	V
B VI	61.05	59.72	58.38	58.19	57.48	57.53	58.07	56.85	59.46	58.85	60.88	58.28	VI
VII	59.26	58.97	58.45	58.55	58.26	58.47	58.01	57.83	58.09	57.86	58.16	58.51	VII
VIII	56.22	55.84	55.81	56.60	56.26	54.98	56.41	56.48	56.40	56.32	57.06	56.75	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
58.63	57.39	56.55	56.67	55.88	55.95	55.90	55.63	57.33	57.45	57.99	56.90

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.16	1.66	1.51	1.93	1.54	1.81	1.44	1.28	1.22	0.94	2.43	1.34

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
53.89	56.62	56.25	57.18	57.56	58.73	58.37	56.26

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
0.92	1.07	1.59	1.74	1.66	1.26	0.41	0.51

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 1.88

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 71.88

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.21

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 56.94

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.10

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.64

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B6. Analysis of density distribution, Test 16

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	52.58	51.23	55.95	54.55	61.40	60.78	61.26	62.30	59.78	57.67	54.59	56.90	I
II	53.01	55.48	56.04	55.90	59.90	62.12	57.47	60.31	57.36	56.75	56.60	57.02	II
S III	56.61	57.52	57.34	56.09	54.04	54.88	54.41	54.26	57.38	57.06	56.80	57.74	III
L IV	57.09	58.28	58.60	57.35	53.49	54.25	53.44	53.29	57.66	56.97	57.28	57.59	IV
A V	58.72	59.87	59.13	58.05	54.97	55.09	54.41	54.60	59.44	58.44	58.74	61.04	V
B VI	60.71	60.73	59.60	59.72	56.33	56.55	56.55	56.82	60.70	60.13	60.01	61.95	VI
VII	62.11	62.93	62.05	62.12	61.93	62.58	61.92	62.63	63.45	61.67	61.66	64.14	VII
VIII	63.73	63.59	62.09	62.19	58.45	59.21	61.13	60.59	64.97	64.20	62.82	64.10	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
58.07	58.70	58.85	58.25	57.56	58.18	57.57	58.10	60.09	59.11	58.56	60.06

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.78	3.79	2.24	2.68	3.11	3.19	3.23	3.55	2.66	2.51	2.60	2.92

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
57.42	57.33	56.18	56.27	57.71	59.15	62.43	62.26

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
3.56	2.33	1.34	1.94	2.21	1.92	0.72	1.97

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.16

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 60.42

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 97.92

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.03

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 58.66

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.03

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.13

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B7. Analysis of density distribution, Test 17

ANALYSIS OF RELATIVE DENSITY DISTRIBUTION

	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
top													
I	59.22	57.25	59.04	59.66	55.17	54.02	54.90	54.82	[illegible]	59.20	60.55	62.12	I
II	63.04	62.56	62.42	62.02	57.40	59.17	54.88	55.03	[illegible]	61.25	62.16	64.12	II
S III	65.58	63.52	62.22	61.87	54.73	55.36	56.33	55.85	64.74	65.19	67.61	64.38	III
L IV	67.60	65.68	65.14	64.91	56.42	54.96	56.60	55.69	68.55	67.13	65.12	65.21	IV
A V	68.71	68.11	68.27	66.62	55.30	55.25	56.36	56.26	70.05	68.21	66.65	67.50	V
B VI	70.64	68.90	68.90	65.71	56.51	56.32	57.34	56.72	69.92	67.47	65.34	67.82	VI
VII	68.45	66.96	67.64	64.50	57.40	57.58	58.70	57.00	67.52	66.38	64.00	64.36	VII
VIII	62.80	62.94	63.76	62.11	54.49	56.53	56.40	55.19	66.00	[illegible]	59.54	61.19	VIII
bottom													

AVERAGE RELATIVE DENSITY OF EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
65.76	64.55	64.67	63.43	55.93	56.21	56.14	56.32	66.16	64.86	63.22	64.76

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.57	3.40	3.23	2.21	1.08	1.50	1.16	0.80	3.38	2.91	2.23	2.18

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
58.07	60.77	61.15	62.90	63.93	64.32	63.38	60.31

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.57	2.79	3.96	4.89	5.75	5.56	4.26	3.62

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 4.76

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 52.08

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 100.00

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.64

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 62.20

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.01

MOMENT COEFFICIENT OF KURTOSIS A4 = 1.68

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B8. Analysis of density distribution, Test 18

ANALYSIS OF RELATIVE [illegible]

[illegible]

		1	2	3	4	5	6	7	8	9	10	11	12	
top														
	I	54.25	55.47	57.08	57.34	60.00	60.31	59.80	59.6[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	I
	II	57.37	57.57	57.28	57.63	58.35	60.51	55.47	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	II
S	III	57.46	57.96	57.17	57.83	55.55	54.5[illegible]	53.5[illegible]	53.7[illegible]	[illegible]	[illegible]	[illegible]	58.[illegible]	III
L	IV	59.68	60.06	58.75	58.01	54.75	55.33	54.36	54.01	[illegible]	[illegible]	[illegible]	[illegible]	IV
A	V	60.85	60.15	59.08	59.20	55.16	55.23	55.41	55.88	[illegible]	[illegible]	[illegible]	[illegible]	V
B	VI	63.61	62.36	62.07	62.99	58.28	58.[illegible]	57.67	58.16	[illegible]	[illegible]	63.31	[illegible]	VI
	VII	64.44	63.26	61.85	62.93	61.13	60.78	61.37	61.[illegible]	64.00	[illegible]	[illegible]	[illegible]	VII
	VIII	61.91	60.90	60.57	61.33	60.10	59.3[illegible]	59.96	[illegible]	[illegible]	61.1[illegible]	[illegible]	65.90	VIII
bottom														

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
59.94	59.72	59.23	59.66	57.92	58.10	57.18	57.47	58.90	59.36	60.00	59.86

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.23	2.42	1.93	2.25	2.32	2.49	2.74	2.55	2.66	2.76	3.10	3.09

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
57.07	57.59	56.46	57.25	58.43	61.23	62.84	60.71

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.20	1.14	1.69	2.01	2.18	2.28	1.50	0.73

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.83

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 61.46

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 97.92

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.98

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 59.08

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.09

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.25

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B9. Analysis of density distribution, Test 19

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	51.53	49.73	52.39	52.77	53.56	53.29	53.64	53.60	54.89	53.04	53.07	54.64	I
II	54.58	51.46	51.43	53.06	49.61	53.08	48.53	49.95	53.68	54.04	53.79	54.80	II
S III	56.67	55.53	55.80	54.74	49.25	50.22	49.57	48.41	53.48	53.95	55.17	55.29	III
L IV	58.35	57.04	55.37	54.20	47.91	48.79	49.49	47.41	54.47	55.16	55.52	56.06	IV
A V	56.90	56.56	53.88	53.79	47.59	47.89	48.14	47.99	53.34	54.13	56.14	57.08	V
B VI	57.35	56.41	54.83	55.67	47.78	47.68	48.60	47.45	54.26	54.45	56.62	57.23	VI
VII	58.78	56.22	55.76	57.19	50.80	50.71	52.40	50.88	56.23	56.33	56.90	58.69	VII
VIII	56.71	54.95	54.74	55.38	50.20	51.26	50.47	49.26	54.26	54.05	54.11	54.15	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
56.36	54.74	54.27	54.60	49.59	50.36	50.11	49.37	54.33	54.38	55.17	55.92

- - STANDARD DEVIATION WITHIN EACH COLUMN -

1	2	3	4	5	6	7	8	9	10	11	12
2.17	2.50	1.50	1.37	1.86	2.02	1.84	1.97	0.87	0.91	1.31	1.33

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB

I	II	III	IV	V	VI	VII	VIII
53.01	52.33	53.17	53.31	52.79	53.19	55.02	54.30

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.31	2.00	2.83	3.66	3.66	3.88	2.85	2.27

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY 3.02

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION 60.42

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 100.00

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.14

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.12

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B10. Analysis of density distribution, Test 20

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	1	2	3	4	5	6	7	8	9	10	11	12	
	COLUMN												
I	52.10	53.68	52.64	51.97	51.73	52.14	51.96	51.93	52.21	51.44	51.22	53.15	I
II	52.10	52.88	52.30	52.29	50.96	52.84	48.58	52.00	54.78	53.21	52.46	56.29	II
S III	52.72	54.28	51.80	51.69	48.59	49.11	49.00	49.15	53.11	52.91	51.76	54.70	III
L IV	54.77	58.16	55.18	53.75	49.20	49.65	48.89	49.80	55.42	53.95	54.63	57.67	IV
A V	56.85	59.32	55.98	54.97	49.80	51.00	48.87	50.23	55.14	53.37	56.96	59.44	V
B VI	60.18	61.29	57.86	58.20	52.38	53.09	64.43	52.84	54.86	54.76	57.94	61.23	VI
VII	55.86	59.55	55.90	56.78	52.47	53.02	51.95	53.12	53.74	53.69	55.64	58.48	VII
VIII	52.10	55.38	53.12	53.08	48.51	50.65	48.38	51.34	50.15	50.02	52.71	53.08	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
54.58	56.82	54.35	54.09	50.46	51.44	51.51	51.30	53.68	52.91	54.17	56.76

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.74	2.95	2.04	2.22	1.53	1.47	5.07	1.35	1.69	1.43	2.34	2.78

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
52.18	52.56	51.57	53.42	54.33	57.42	55.02	51.54

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
0.67	1.79	2.04	3.12	3.50	3.72	2.32	2.00

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.19

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 66.67

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.56

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 53.83

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.80

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.67

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B11. Analysis of density distribution, Test 21

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

		COLUMN											
top	1	2	3	4	5	6	7	8	9	10	11	12	
I	54.74	56.79	55.89	54.82	55.65	56.71	54.73	54.74	53.14	52.82	56.17	54.31	I
II	55.03	60.88	58.00	55.62	52.99	57.58	50.47	51.03	51.27	52.58	55.03	54.35	II
S III	52.77	57.30	52.62	51.40	47.89	50.24	48.09	46.54	48.78	49.73	51.25	50.56	III
L IV	49.39	50.02	50.43	51.39	45.21	45.75	44.48	44.29	49.02	49.68	50.21	50.05	IV
A V	48.47	49.68	47.83	49.92	44.02	44.04	43.68	44.17	49.67	50.86	50.54	50.30	V
B VI	48.32	50.48	48.38	50.98	46.17	45.19	44.81	46.00	51.20	51.85	53.18	51.98	VI
VII	49.14	50.94	50.88	49.57	48.35	50.03	48.37	47.72	51.31	52.96	51.84	50.85	VII
VIII	49.48	49.63	49.29	50.44	47.45	48.82	47.56	46.16	50.21	50.71	50.15	48.92	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
50.92	53.21	51.66	51.77	48.47	49.80	47.77	47.58	50.58	51.40	52.30	51.42

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.63	4.13	3.40	2.09	3.69	4.75	3.40	3.38	1.35	1.25	2.14	1.86

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
55.04	54.57	50.60	48.33	47.76	49.04	50.16	49.07

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.21	3.01	2.72	2.49	2.80	2.82	1.51	1.32

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.49

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 66.67

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.89

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 50.78

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.27

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.03

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B12. Analysis of density distribution, Test 22

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	56.22	57.94	54.64	53.34	51.06	51.67	52.35	51.63	52.49	52.44	55.43	55.94	I
II	56.23	55.97	53.06	53.53	49.51	52.02	47.68	[illegible]	56.11	56.33	55.86	56.39	II
S III	59.38	60.42	56.04	55.71	48.16	49.08	50.11	48.90	[illegible]	58.71	55.78	56.97	III
L IV	62.17	61.57	56.36	56.68	47.67	47.15	49.24	48.47	52.72	59.63	58.33	60.11	IV
A V	63.76	66.14	60.88	59.67	49.08	49.65	49.94	49.01	57.95	59.56	61.52	62.68	V
B VI	64.83	69.37	63.42	64.46	54.44	54.97	49.33	[illegible]	62.16	62.86	66.44	64.84	VI
VII	63.62	69.25	63.02	61.05	53.95	55.50	54.78	54.95	59.62	61.05	63.95	65.51	VII
VIII	61.00	66.06	61.15	60.18	54.00	55.34	54.59	53.41	57.91	59.62	60.65	60.29	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
60.90	63.34	58.57	58.08	50.98	51.92	51.00	51.92	58.12	59.40	59.74	59.96

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.14	4.77	3.75	3.66	2.61	2.95	2.45	3.45	1.85	1.89	3.84	3.08

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
54.59	53.60	54.61	55.42	57.49	61.38	60.19	58.68

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.39	2.93	4.19	5.43	6.05	5.54	4.59	3.58

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 5.25

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 63.54

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 97.92

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.14

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 57.61

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.06

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.36

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B13. Analysis of density distribution, Test 23

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	72.34	72.44	75.62	76.54	78.92	77.21	77.71	79.04	76.08	74.60	76.49	77.39	I
II	72.15	73.08	76.37	77.60	79.98	78.93	78.83	80.31	77.13	75.35	77.51	77.91	II
S III	70.53	72.96	75.00	76.03	79.15	77.53	77.53	79.45	74.30	73.19	75.41	75.59	III
L IV	69.58	72.24	74.89	75.68	78.69	77.27	76.43	78.10	73.11	71.57	74.80	74.05	IV
A V	71.04	73.66	74.96	74.68	77.88	77.92	76.67	77.45	72.18	69.97	74.26	73.66	V
B VI	70.16	73.36	75.09	74.70	77.62	77.56	76.29	76.87	72.57	71.88	73.06	72.81	VI
VII	72.84	75.67	76.70	76.32	78.93	79.42	78.34	78.76	73.77	73.62	75.01	74.40	VII
VIII	73.78	77.38	77.52	76.10	78.59	79.53	77.71	78.16	72.47	72.81	74.84	73.63	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
71.57	73.85	75.77	75.96	78.72	78.17	77.44	78.52	73.95	72.87	75.17	74.93

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.35	1.66	0.92	0.90	0.69	0.91	0.85	1.04	1.68	1.62	1.27	1.74

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
76.20	77.10	75.56	74.70	74.53	74.33	76.15	76.04

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.09	2.42	2.49	2.63	2.52	2.30	2.20	2.34

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.55

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 22.19

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 75.43

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.27

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.21

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B14. Analysis of density distribution, Test 38

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	70.85	69.38	70.03	72.17	73.99	73.03	71.51	70.88	73.29	74.62	72.72	70.16	I
II	69.82	67.80	69.39	70.92	75.45	73.47	73.23	74.71	71.59	70.15	72.02	72.14	II
S III	70.05	69.78	71.14	72.54	77.45	76.20	75.87	77.71	75.55	72.65	73.81	74.78	III
L IV	72.39	71.88	72.97	73.71	78.06	77.29	77.67	79.02	77.32	76.09	74.66	75.29	IV
A V	72.16	70.90	72.24	73.23	77.70	77.34	77.64	79.21	77.56	76.38	75.34	75.88	V
B VI	72.65	69.60	71.62	73.50	77.97	76.53	77.68	79.36	77.59	76.82	74.96	75.91	VI
VII	73.12	71.74	72.54	73.90	78.72	77.52	78.26	80.35	79.34	77.69	75.92	78.15	VII
VIII	71.72	70.21	70.68	72.12	76.87	75.66	76.80	78.61	78.38	76.37	73.47	76.71	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
71.59	70.16	71.33	72.76	77.03	75.88	76.08	77.48	76.33	75.09	74.11	74.88

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.15	1.26	1.17	0.95	1.47	1.63	2.29	2.95	2.49	2.36	1.26	2.40

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
71.88	71.72	73.96	75.53	75.47	75.35	76.44	74.80

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.61	2.16	2.62	2.30	2.58	2.82	2.78	2.87

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.99

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 59.38

PERCENT OF ELFMENTS WITHIN TWO STANDARD DEVIATION = 98.96

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 22.30

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 74.34

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.05

MOMENT COEFFICIENT OF KURTOSIS A4 = 1.89

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B15. Analysis of density distribution, Test 39

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	62.26	60.48	60.00	59.20	66.11	65.60	67.62	68.48	66.21	65.16	60.85	65.02	I
II	66.73	66.44	66.11	63.72	70.15	70.13	71.20	71.87	70.07	68.26	63.67	67.59	II
S III	65.68	66.46	65.14	62.72	68.60	69.10	70.12	69.76	68.02	67.29	62.72	64.92	III
L IV	66.61	67.46	67.74	66.01	71.13	70.69	70.95	71.75	68.31	66.63	65.54	67.06	IV
A V	66.95	68.27	67.67	65.22	71.10	71.66	70.86	71.32	67.15	67.38	66.11	67.00	V
B VI	68.20	70.46	70.48	68.82	72.06	73.54	72.35	71.97	67.90	67.84	67.13	67.14	VI
VII	70.31	71.25	70.34	69.60	73.11	74.07	73.34	72.88	68.55	65.63	69.42	68.50	VII
VIII	66.41	68.43	68.34	68.99	69.60	70.86	69.43	69.52	65.82	65.68	66.54	64.74	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
66.64	67.40	66.98	65.54	70.23	70.71	70.73	70.95	67.75	66.73	65.25	66.50

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.13	3.08	3.15	3.37	2.04	2.48	1.64	1.41	1.27	1.07	2.54	1.32

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
63.92	67.99	66.71	68.32	68.39	69.82	70.58	67.86

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
3.05	2.64	2.43	2.11	2.14	2.17	2.37	1.86

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.03

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 72.92

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.02

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 67.86

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.47

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.28

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B16. Analysis of density distribution, Test 40

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	66.64	62.46	64.95	66.17	71.91	71.91	71.93	71.62	64.20	67.24	67.17	63.16	I
II	70.03	67.65	70.70	71.91	74.98	74.06	74.08	74.03	67.65	70.67	71.48	66.60	II
S III	70.45	69.48	72.00	72.82	76.05	75.61	74.82	75.05	69.85	70.99	71.81	69.26	III
L IV	71.15	70.67	72.26	72.30	76.18	76.62	76.29	76.09	70.43	71.90	71.72	69.75	IV
A V	71.38	69.58	71.01	70.68	75.38	76.31	76.48	75.61	70.61	72.00	69.55	68.78	V
B VI	71.83	70.52	71.27	71.37	75.18	75.99	75.77	74.40	69.81	71.42	69.36	68.21	VI
VII	71.08	70.62	71.55	71.55	75.76	75.47	75.72	75.82	70.83	73.08	70.00	68.45	VII
VIII	70.60	70.72	70.75	71.36	73.95	73.30	73.23	73.48	71.11	72.18	71.64	70.93	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
70.39	68.96	70.56	71.02	74.92	74.91	74.79	74.51	69.31	71.18	70.34	68.14

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.51	2.64	2.19	1.93	1.32	1.55	1.50	1.38	2.18	1.64	1.53	2.22

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
67.45	71.15	72.35	72.95	72.28	72.09	72.49	71.94

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
3.41	2.70	2.38	2.47	2.73	2.51	2.48	1.18

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.03

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 65.63

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 22.62

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 71.43

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.49

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.39

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B17. Analysis of density distribution, Test 41

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	71.39	70.36	73.64	73.38	79.52	79.64	79.42	79.06	71.58	72.49	73.[illegible]8	70.83	I
II	72.12	72.23	75.34	75.46	79.76	79.32	78.92	78.81	73.73	73.58	74.49	72.66	II
S III	71.63	71.55	74.30	74.51	78.10	77.32	76.70	76.49	71.78	71.15	72.64	71.46	III
L IV	67.60	66.97	69.10	69.35	73.43	72.85	72.75	72.25	67.68	68.28	68.70	67.41	IV
A V	69.43	69.65	71.25	70.63	74.68	74.76	73.78	73.60	69.5[illegible]	69.56	69.39	67.96	V
B VI	70.11	71.22	71.98	72.14	75.49	75.66	75.13	74.55	69.58	69.50	69.33	68.54	VI
VII	71.80	72.13	73.74	73.13	77.84	78.16	77.83	77.22	71.50	71.52	70.89	70.22	VII
VIII	71.25	70.58	71.85	72.25	76.43	75.10	75.17	74.94	70.97	71.63	70.44	69.51	VIII
bottom													

- AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
70.67	70.59	72.65	72.61	76.91	76.60	76.22	75.86	70.79	70.96	71.15	69.82

- - STANDARD DEVIATION WITHIN EACH COLUMN -

1	2	3	4	5	6	7	8	9	10	11	12
1.43	1.60	1.86	1.86	2.14	2.24	2.25	2.29	1.71	1.63	1.96	1.69

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
74.55	75.53	73.97	69.70	71.19	71.94	73.83	72.51

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
3.57	2.79	2.49	2.32	2.28	2.54	2.92	2.19

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.22

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 62.50

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 22.49

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 72.68

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.45

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.45

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B18. Analysis of density distribution, Test 42

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

SLAB	1	2	3	4	5	6	7	8	9	10	11	12	
top I	59.23	58.64	59.26	59.41	69.45	69.28	67.50	68.34	60.09	59.06	58.95	57.58	I
II	61.62	61.81	63.84	64.86	69.55	68.50	68.83	70.36	65.58	64.11	64.46	65.12	II
III	62.13	62.01	64.69	66.29	69.85	68.01	68.15	70.09	65.36	64.31	66.11	65.74	III
IV	59.55	60.21	64.03	64.99	68.57	66.11	65.79	68.13	64.58	62.10	65.41	65.31	IV
V	59.76	61.45	64.80	65.65	68.63	67.21	65.97	67.68	63.26	61.76	65.27	64.05	V
VI	59.01	60.17	64.69	65.02	68.20	65.84	64.93	66.74	62.09	61.55	64.03	63.84	VI
VII	63.32	63.74	66.72	67.70	72.33	70.96	70.05	71.15	65.24	64.67	67.57	65.99	VII
VIII bottom	63.12	64.32	66.54	67.16	70.80	69.26	67.55	68.68	64.07	62.84	67.28	65.60	VIII

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
60.97	61.54	64.32	65.13	69.67	68.15	67.35	68.90	63.79	62.55	64.89	64.15

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.67	1.76	2.15	2.38	1.27	1.62	1.59	1.40	1.78	1.74	2.52	2.59

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
62.23	65.72	66.06	64.57	64.63	63.84	67.45	66.43

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
4.59	2.81	2.52	2.65	2.57	2.58	2.93	2.40

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.33

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 97.92

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.32

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 65.11

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.22

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.44

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII and each slab cut into segments labeled 1, 2, ... 12

Figure B19. Analysis of density distribution, Test 43

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	56.15	54.81	55.89	55.17	72.58	70.79	71.93	71.36	55.34	56.95	57.78	55.35	I
II	57.45	55.52	57.52	57.79	61.06	62.01	61.32	59.97	56.57	56.29	55.09	56.15	II
S III	58.60	57.54	59.03	58.93	58.65	58.29	60.63	59.85	60.91	60.84	59.00	60.34	III
L IV	60.00	59.64	60.78	61.00	60.97	60.83	61.05	60.40	62.43	63.08	61.14	61.86	IV
A V	60.19	60.74	62.83	62.66	62.58	62.78	61.48	61.37	62.22	61.78	62.28	62.35	V
B VI	63.07	63.34	64.33	64.60	64.90	64.25	64.09	64.73	64.33	63.61	63.78	63.75	VI
VII	64.33	65.43	66.74	66.81	70.91	71.35	69.80	69.76	64.64	64.28	66.05	64.68	VII
VIII	68.79	68.58	68.21	68.34	73.46	73.23	73.04	73.44	69.01	68.27	68.59	68.94	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
61.07	60.70	61.92	61.91	65.64	65.44	65.42	65.11	61.93	61.89	61.71	61.68

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.87	4.53	4.10	4.26	5.46	5.21	4.95	5.25	4.14	3.67	4.15	4.17

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
61.18	58.06	59.38	61.10	61.94	64.07	67.07	70.16

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
7.47	2.31	1.06	0.93	0.81	0.54	2.56	2.23

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 4.87

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 61.46

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.58

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 62.76

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.45

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.47

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B20. Analysis of density distribution, Test 44

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	57.01	55.32	55.15	58.87	72.50	70.48	71.58	71.73	57.28	58.62	57.83	53.00	I
II	56.04	56.61	58.29	56.83	61.25	61.87	61.26	61.39	56.82	57.48	56.17	56.10	II
S III	54.87	57.78	57.38	56.68	59.26	59.06	59.09	59.50	59.62	58.48	56.95	51.92	III
L IV	58.44	58.61	59.44	59.17	59.35	59.58	59.40	58.64	60.03	59.90	59.77	58.97	IV
A V	60.08	60.52	61.81	62.02	60.97	61.00	61.32	60.93	60.83	60.67	61.96	61.17	V
B VI	62.07	63.14	64.85	63.52	63.87	64.16	63.94	64.07	64.15	63.02	63.36	62.89	VI
VII	64.04	65.34	67.25	66.46	71.53	70.97	71.26	71.75	67.67	66.15	66.97	66.60	VII
VIII	67.87	68.11	69.58	69.64	73.51	73.37	73.37	73.87	71.23	69.99	70.08	70.54	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
60.05	60.68	61.72	61.65	65.28	65.06	65.15	65.23	62.20	61.76	61.64	60.15

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
4.12	4.20	4.76	4.36	5.78	5.33	5.56	5.81	4.77	4.09	4.64	6.07

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
61.61	58.34	57.54	59.28	61.11	63.59	68.00	70.93

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
7.22	2.28	2.17	0.50	0.57	0.71	2.55	2.04

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 5.38

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 65.63

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.63

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 62.28

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.52

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.29

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B21. Analysis of density distribution, Test 45

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	68.07	79.31	67.76	74.90	65.64	66.12	64.45	64.68	60.04	65.82	62.85	72.38	I
II	58.99	60.77	61.42	61.23	65.48	65.90	63.56	64.13	57.66	57.50	57.19	56.59	II
S III	58.60	60.03	61.48	61.72	64.31	64.11	61.92	61.88	57.64	57.41	58.66	57.66	III
L IV	58.94	60.14	61.51	61.97	63.44	63.88	61.83	61.02	57.45	57.93	60.13	57.76	IV
A V	59.44	60.51	61.48	61.78	63.29	63.44	62.00	62.55	60.12	59.53	60.30	59.85	V
B VI	63.99	64.13	64.45	64.06	67.11	66.94	66.76	66.51	64.60	64.06	63.29	64.28	VI
VII	65.44	64.83	64.12	64.32	69.17	69.03	69.26	70.23	65.69	66.86	64.93	65.99	VII
VIII	68.57	64.52	63.01	63.39	67.81	67.47	67.17	67.71	68.95	70.64	64.79	67.63	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
62.76	64.28	63.16	64.17	65.78	65.87	64.62	64.84	61.52	62.47	62.14	62.77

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
4.00	6.00	2.10	4.20	1.98	1.83	2.64	2.94	4.07	4.74	3.41	5.32

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
68.09	60.87	60.45	60.50	61.19	65.01	66.66	66.81

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
4.96	3.19	2.36	2.07	1.37	1.33	2.09	2.25

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 4.07

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 69.79

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.49

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 63.58

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.69

MOMENT COEFFICIENT OF KURTOSIS A4 = 4.26

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B22. Analysis of density distribution, Test 46

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	70.27	70.71	69.28	69.27	74.05	75.13	77.85	73.43	66.30	66.73	67.98	66.00	I
II	71.86	70.76	71.53	69.74	72.78	72.51	72.16	70.10	65.40	66.66	65.80	65.45	II
S III	75.05	73.69	71.26	69.78	76.87	77.89	78.54	76.52	70.09	73.47	70.57	70.83	III
L IV	78.62	76.62	74.84	74.35	79.17	79.57	80.54	78.43	76.04	76.81	74.81	73.39	IV
A V	78.70	77.26	75.73	75.37	79.28	80.04	80.69	79.53	76.96	77.94	76.23	75.54	V
B VI	79.84	79.52	78.22	77.99	79.54	78.96	79.12	78.82	78.88	78.80	79.03	77.94	VI
VII	79.28	78.09	77.46	77.90	79.02	78.27	81.00	78.22	79.02	79.03	78.81	77.45	VII
VIII	75.65	75.49	76.14	76.18	80.97	80.89	80.86	78.04	77.02	76.45	76.65	77.12	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
76.16	75.27	74.31	73.82	77.71	77.91	78.84	76.64	73.71	74.49	73.74	72.97

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.36	3.07	3.02	3.46	2.71	2.61	2.76	3.04	5.23	4.78	4.69	4.72

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
70.58	69.56	73.71	76.93	77.77	78.89	78.63	77.62

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
3.63	2.79	3.07	2.22	1.78	0.57	0.93	2.00

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 4.17

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 70.83

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 92.71

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 22.19

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 75.38

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.86

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.73

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B23. Analysis of density distribution, Test 47

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	42.88	39.83	43.41	45.89	39.04	37.27	37.19	37.69	43.38	44.17	45.38	43.10	I
II	39.86	37.28	39.83	42.12	37.34	35.24	36.09	36.17	39.99	41.81	41.36	38.44	II
S III	42.75	40.04	42.05	43.51	38.91	36.09	38.04	38.26	43.12	43.96	43.02	41.26	III
L IV	42.47	41.44	45.31	47.32	41.70	39.73	40.02	40.56	44.42	42.70	45.15	42.98	IV
A V	38.49	36.68	39.12	40.51	37.52	36.26	36.03	36.28	39.12	39.17	38.88	37.48	V
B VI	35.51	32.99	36.18	38.43	38.08	35.43	36.08	36.83	36.54	36.06	37.80	35.45	VI
VII	33.97	33.02	36.07	37.57	37.19	35.50	35.39	35.23	34.74	34.77	36.72	33.35	VII
VIII	37.43	36.51	38.34	39.24	38.46	37.46	35.07	37.05	37.83	37.86	38.84	37.23	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
39.17	37.22	40.04	41.82	38.53	36.62	36.74	37.26	39.89	40.30	40.89	38.66

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.20	2.93	3.12	3.31	1.36	1.40	1.52	1.52	3.22	3.63	3.13	3.30

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
41.60	38.79	40.91	42.98	37.96	36.28	35.29	37.61

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
3.07	2.27	2.47	2.30	1.39	1.40	1.38	1.07

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.23

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 65.63

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 26.19

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 38.99

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.51

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.48

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B24. Analysis of density distribution, Test 49

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

SLAB	1	2	3	4	5	6	7	8	9	10	11	12	
top													
I	44.11	46.58	47.84	48.06	46.53	46.51	47.64	49.46	50.16	49.10	47.04	48.90	I
II	45.67	46.00	47.97	48.72	49.14	46.94	49.89	51.36	48.63	49.63	48.85	50.54	II
III	44.43	45.71	47.96	51.[illegible]6	49.25	46.62	46.36	47.99	49.84	47.34	48.92	50.02	III
IV	44.62	45.70	45.62	45.46	46.91	45.80	46.98	48.20	49.48	46.81	46.33	49.21	IV
V	43.14	46.58	47.84	46.20	44.95	45.42	44.57	45.64	46.30	45.44	44.23	46.21	V
VI	44.64	48.30	50.64	48.76	46.60	47.55	46.35	47.68	50.16	48.13	44.58	48.03	VI
VII	45.34	48.12	50.83	50.08	47.72	48.00	46.60	48.14	50.48	48.13	46.65	48.90	VII
VIII	42.78	45.34	48.00	46.79	45.32	44.70	43.58	45.23	47.72	45.00	45.06	47.32	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
44.34	46.54	48.34	48.23	47.12	46.44	46.50	47.96	49.10	47.45	46.38	48.63

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
0.93	1.04	1.57	1.95	1.58	1.03	1.78	1.83	1.36	1.53	1.68	1.32

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
47.65	48.61	48.06	46.76	45.54	47.62	48.20	45.57

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.58	1.66	2.01	1.45	1.18	1.79	1.63	1.54

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 1.96

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 67.71

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 25.28

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 47.20

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.07

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.37

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B25. Analysis of density distribution, Test 50

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

SLAB		1	2	3	4	5	6	7	8	9	10	11	12	
top														
	I	46.25	47.91	50.20	47.53	41.41	45.12	46.62	45.02	47.50	50.[illegible]	47.91	40.99	I
	II	45.71	47.58	49.88	49.27	42.51	48.69	46.42	46.12	47.60	49.30	49.23	41.70	II
S	III	46.41	40.14	42.26	47.40	43.58	41.30	44.09	43.52	47.96	45.83	47.22	45.16	III
L	IV	48.08	45.79	50.82	48.84	50.92	49.24	48.32	49.06	49.51	48.58	48.02	49.76	IV
A	V	49.94	47.23	49.25	50.24	47.48	47.56	47.38	46.93	50.13	50.99	49.55	47.55	V
B	VI	50.39	47.48	49.87	48.28	48.04	47.25	47.46	46.19	49.66	49.18	49.96	46.96	VI
	VII	46.37	43.49	47.57	48.99	45.36	45.16	45.28	44.25	47.30	48.25	45.81	43.14	VII
	VIII	46.48	44.69	46.30	47.31	45.05	45.09	44.83	43.66	46.01	48.03	44.18	42.51	VIII
bottom														

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
47.45	45.54	48.27	48.48	45.55	46.18	46.36	45.60	48.20	49.12	47.73	44.72

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.69	2.51	2.66	0.98	2.96	2.40	1.32	1.26	1.33	1.02	1.84	2.94

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
46.39	47.05	44.73	48.92	48.68	48.39	45.95	45.35

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.80	2.60	2.55	1.32	1.40	1.32	1.76	1.49

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.49

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 65.63

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.63

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.85

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B26. Analysis of density distribution, Test 51

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	17.27	6.23	8.83	22.88	28.23	27.98	26.37	24.29	14.39	15.20	20.13	17.66	I
II	46.05	45.79	42.57	39.90	56.68	50.80	56.96	58.77	46.93	41.43	39.95	42.05	II
S III	51.17	46.67	47.59	50.44	55.95	55.64	55.97	56.79	50.80	48.49	48.72	48.75	III
L IV	52.05	52.62	53.34	53.95	53.79	52.45	52.24	53.41	53.94	52.67	54.91	54.38	IV
A V	54.94	55.83	56.64	56.46	52.36	51.27	50.14	50.73	55.61	54.88	57.36	56.86	V
B VI	56.59	57.48	58.32	58.46	51.63	51.11	50.47	51.43	56.40	56.16	58.57	57.88	VI
VII	58.02	58.61	58.24	59.16	57.35	56.95	56.53	56.89	57.23	56.49	60.12	59.25	VII
VIII	55.78	54.27	54.23	54.13	56.43	56.82	56.55	55.76	53.15	53.92	53.07	52.37	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
48.98	47.19	47.47	49.42	51.55	50.38	50.65	51.00	48.61	47.41	49.11	48.65

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
12.50	16.09	15.47	11.54	9.03	8.80	9.55	10.46	13.30	13.04	12.51	12.82

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
19,12	47.32	51.42	53.31	54.42	55.38	57.90	54.74

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
6.89	6.60	3.53	0.87	2.48	3.08	1.14	1.41

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 12.38

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION 87.50

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 90.63

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST 25.07

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST 49.14

MOMENT COEFFICIENT OF SKEWNESS, A3 = -1.98

MOMENT COEFFICIENT OF KURTOSIS A4 = 5.93

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B27. Analysis of density distribution, Test 52

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	32.39	26.38	31.63	35.50	45.66	44.70	47.38	44.52	38.62	38.01	30.76	31.87	I
II	38.99	37.43	35.51	35.38	41.68	41.32	42.20	40.47	37.75	38.25	40.15	37.60	II
S III	43.62	44.75	44.03	43.46	45.09	43.68	44.55	44.26	43.58	43.35	46.37	43.75	III
L IV	48.33	46.67	48.22	48.12	46.67	46.53	45.21	44.76	46.24	44.64	47.93	45.66	IV
A V	49.10	48.46	46.33	45.55	47.61	47.55	47.97	47.08	47.02	46.79	47.62	47.08	V
B VI	49.93	45.44	44.47	43.95	49.04	47.99	50.73	48.14	47.88	48.35	45.11	45.62	VI
VII	52.22	49.63	48.22	47.20	52.41	51.60	53.58	50.85	48.63	49.14	48.01	47.88	VII
VIII	53.28	50.71	49.58	48.50	52.16	51.35	54.20	51.78	51.38	52.29	49.06	48.80	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
45.98	43.68	43.50	43.46	47.54	46.84	48.23	46.48	45.14	45.35	44.38	43.53

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
6.73	7.58	6.08	4.93	3.39	3.35	4.03	3.50	4.51	4.79	5.77	5.47

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
37.28	38.89	44.21	46.75	47.35	47.22	49.95	51.09

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
6.66	2.20	0.84	1.15	0.90	2.13	2.02	1.74

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 5.42

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 71.88

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST 25.50

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 45.22

MOMENT COEFFICIENT OF SKEWNESS, A3 = -1.16

MOMENT COEFFICIENT OF KURTOSIS A4 = 4.30

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B28. Analysis of density distribution, Test 53

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	30.13	30.73	25.58	28.65	43.96	44.31	43.17	44.66	[illegible]	[illegible]	33.24	33.78	I
II	33.14	34.81	35.87	33.66	34.92	35.67	36.16	36.50	35.14	[illegible]	33.53	36.14	II
S III	41.38	43.56	43.85	42.30	44.71	44.10	43.74	44.39	43.19	43.15	42.28	42.88	III
L IV	46.37	48.42	49.99	52.49	50.45	48.02	47.20	48.64	48.19	48.07	51.07	48.53	IV
A V	45.32	46.50	47.48	46.88	45.58	45.52	45.09	45.77	47.22	46.97	48.10	48.72	V
B VI	43.32	44.64	45.14	44.70	45.38	45.75	44.77	46.19	45.12	44.73	45.86	46.34	VI
VII	48.64	49.88	49.51	49.88	52.72	52.81	51.97	53.58	50.73	49.09	50.59	51.38	VII
VIII	47.31	49.86	50.30	50.98	52.25	52.20	49.90	51.72	49.67	47.29	50.21	50.15	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
41.95	43.55	43.47	43.69	46.25	46.05	45.25	46.43	44.39	43.20	44.42	44.74

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
6.36	6.66	8.08	7.98	5.39	5.03	4.47	4.88	5.73	6.07	6.87	6.16

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
35.51	34.94	43.33	48.95	46.64	45.16	50.90	50.15

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
6.49	1.12	0.89	1.66	1.15	0.79	1.53	1.54

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 6.37

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 67.71

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 25.59

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 44.42

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.96

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.06

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B29. Analysis of density distribution, Test 54

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	21.76	15.73	24.11	28.95	40.70	36.79	37.74	40.18	29.32	27.96	28.43	28.42	I
II	27.73	24.99	27.70	28.89	32.54	31.79	31.72	31.89	28.53	28.44	29.50	28.96	II
S III	39.30	37.27	37.38	37.22	42.18	42.10	42.84	42.56	39.38	39.89	37.20	25.34	III
L IV	43.06	42.75	44.72	44.92	45.86	45.69	44.91	45.16	44.75	44.38	43.84	43.71	IV
A V	45.85	46.12	48.18	48.15	48.20	47.45	47.21	47.48	48.73	47.40	47.15	47.48	V
B VI	48.86	48.97	50.07	49.61	50.99	51.06	50.79	51.68	51.98	50.90	48.76	50.52	VI
VII	49.08	49.33	50.12	49.60	51.59	51.57	51.47	52.22	50.82	49.77	48.88	49.81	VII
VIII	50.58	49.73	51.42	51.16	50.95	51.51	51.34	51.56	52.23	51.31	49.53	50.56	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
40.78	39.36	41.71	42.31	45.38	44.74	44.75	45.34	43.22	42.51	41.66	40.60

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
9.97	11.86	10.07	8.73	6.19	6.88	6.65	6.58	9.16	8.97	8.23	10.35

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
30.01	29.39	38.56	44.48	47.45	50.35	50.36	50.99

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
7.31	2.13	4.51	0.93	0.80	1.05	1.08	0.74

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 9.01

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 75.00

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 25.78

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 42.65

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.94

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.73

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B30. Analysis of density distribution, Test 55

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	24.00	17.44	22.18	28.10	40.44	32.41	39.60	42.13	31.94	29.11	31.15	31.60	I
II	29.24	29.17	29.08	31.31	32.82	30.58	30.24	32.55	31.04	30.13	33.18	32.86	II
S III	46.91	46.06	38.50	39.02	41.83	44.88	45.25	41.69	40.57	42.60	40.48	40.14	III
L IV	49.46	47.18	46.32	46.51	47.45	47.21	49.18	46.45	46.62	48.30	46.53	44.83	IV
A V	44.48	44.31	47.43	48.76	48.03	46.76	47.03	47.16	47.27	47.08	47.64	46.12	V
B VI	50.83	50.43	51.99	52.01	51.92	52.70	52.47	51.68	50.83	51.84	50.57	48.61	VI
VII	51.96	51.24	53.53	53.98	54.58	54.17	53.98	53.64	51.95	52.78	51.69	50.09	VII
VIII	53.57	52.82	53.59	54.63	56.11	55.19	55.30	55.54	53.87	53.82	55.31	53.90	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
43.81	42.33	42.83	44.29	46.65	45.49	46.63	46.36	44.26	44.46	44.57	43.52

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
10.35	11.67	11.08	9.64	7.38	8.80	7.83	7.04	8.29	9.20	8.23	7.52

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
30.84	31.02	42.33	47.17	46.84	51.32	52.80	54.47

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
7.14	1.46	2.70	1.24	1.26	1.08	1.34	0.97

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 9.14

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 25.55

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 44.80

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.89

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.80

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B31. Analysis of density distribution, Test 56

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	51.88	54.87	61.80	61.60	66.98	66.40	63.73	63.68	46.15	52.89	51.02	42.79	I
II	79.25	65.68	63.67	59.88	71.39	76.17	77.27	72.63	67.17	68.69	56.02	57.84	II
S III	59.59	62.31	62.91	57.02	65.55	71.72	68.28	61.20	52.73	57.72	50.84	48.39	III
L IV	58.94	58.45	57.79	54.32	65.88	68.86	67.22	64.40	54.44	56.35	51.98	48.44	IV
A V	60.21	60.70	63.22	63.38	71.51	70.46	68.30	68.03	55.42	59.10	61.62	58.28	V
B VI	54.99	56.47	58.86	58.03	64.54	66.44	62.41	58.71	47.12	46.75	52.96	48.33	VI
VII	55.67	55.80	54.93	57.07	69.52	72.51	69.27	68.58	59.68	56.70	53.85	53.56	VII
VIII	41.89	47.87	53.87	54.09	68.31	68.04	62.26	62.94	42.47	36.48	48.33	46.63	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
57.80	57.77	59.63	58.17	67.96	70.07	67.34	65.02	53.15	54.33	53.33	50.53

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
9.82	5.05	3.60	3.08	2.49	3.13	4.57	4.19	7.46	8.86	3.79	5.14

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
56.98	67.97	59.85	58.92	63.35	56.30	60.60	52.76

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
7.77	7.36	6.69	6.15	4.92	6.29	6.85	10.17

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 8.38

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 93.75

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.97

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 59.17

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.17

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.79

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B32. Analysis of density distribution, Test 57

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
top													
I	48.06	46.60	52.37	54.07	65.51	64.34	63.51	63.23	52.47	55.26	50.47	49.56	I
II	57.07	57.34	59.19	59.46	68.79	69.13	70.11	68.69	60.41	61.46	56.55	55.29	II
S III	59.66	58.27	54.27	52.94	65.04	67.54	68.00	67.46	60.36	61.01	51.45	53.26	III
L IV	62.94	64.49	64.36	65.04	73.56	72.98	71.58	70.62	60.72	61.48	61.10	60.37	IV
A V	65.72	58.59	71.17	67.70	74.74	77.28	74.35	72.49	61.36	62.92	60.36	60.48	V
B VI	58.33	62.63	68.29	66.36	72.49	73.83	69.27	68.98	57.70	58.13	60.54	57.86	VI
VII	56.76	56.84	57.54	56.61	68.31	65.53	66.72	64.05	54.53	56.02	54.05	55.40	VII
VIII	53.69	52.46	55.53	52.71	63.05	65.54	63.19	60.22	49.60	50.85	48.66	46.82	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
57.78	57.15	60.34	59.36	68.94	69.52	68.34	66.97	57.14	58.39	55.40	54.88

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
5.08	5.25	6.42	5.83	4.03	4.38	3.59	3.86	4.14	3.85	4.64	4.57

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
55.46	61.96	59.94	65.77	67.26	64.53	59.36	55.19

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
6.57	5.37	5.83	4.80	6.29	5.77	4.97	6.04

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 7.13

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 63.54

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 96.88

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.80

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 60.76

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.07

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.29

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B33. Analysis of density distribution, Test 58

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	49.82	47.29	51.89	55.26	65.98	65.60	67.33	67.45	58.17	57.86	54.23	56.41	I
II	55.39	54.50	57.38	56.01	60.81	60.79	61.40	60.70	53.25	53.62	51.85	53.32	II
S III	58.04	61.51	65.61	63.71	68.93	69.39	65.10	63.38	55.88	56.18	58.40	57.04	III
L IV	56.99	57.69	62.76	63.01	69.54	67.94	66.65	67.44	59.93	58.78	62.70	60.74	IV
A V	61.67	62.76	63.65	63.59	74.28	72.06	71.24	72.75	63.83	63.28	64.12	64.35	V
B VI	47.32	45.83	48.33	52.49	65.99	60.92	59.72	65.65	56.31	52.22	59.06	60.45	VI
VII	53.34	53.57	56.56	57.75	64.85	64.82	65.34	65.48	57.14	55.35	56.84	57.40	VII
VIII	39.22	41.92	54.57	57.06	65.00	60.57	56.99	62.38	48.59	45.69	55.15	51.50	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
52.72	53.13	57.59	58.61	66.92	65.26	64.22	65.65	56.64	55.37	57.79	57.65

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
6.65	7.06	5.66	4.01	3.74	4.05	4.29	3.49	4.21	4.85	3.91	3.89

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
58.11	56.59	61.93	62.85	66.47	56.19	59.04	53.22

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
6.71	3.36	4.61	4.05	4.42	6.61	4.50	7.72

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 6.74

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 72.92

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.99

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 58.96

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.35

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.14

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B34. Analysis of density distribution, Test 59

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	56.10	56.33	57.02	57.31	66.18	66.29	67.43	69.05	58.92	58.59	59.06	57.94	I
II	63.09	64.20	64.91	65.20	66.28	67.24	65.62	64.44	61.26	62.85	62.71	61.63	II
S III	60.15	61.01	60.95	60.76	63.63	64.67	62.01	61.34	58.90	59.53	58.92	60.22	III
L IV	64.70	63.17	66.33	65.49	69.74	71.08	69.15	69.26	63.82	62.04	64.02	64.11	IV
A V	61.98	62.42	64.04	62.55	64.34	66.31	64.45	61.24	58.21	60.80	58.14	57.72	V
B VI	59.41	60.29	59.11	58.18	57.55	60.31	59.26	57.22	58.61	59.70	56.70	57.05	VI
VII	58.75	58.70	58.47	57.80	59.62	59.04	60.19	61.17	58.82	59.09	57.51	57.70	VII
VIII	54.08	53.49	54.41	53.63	53.98	56.30	57.94	54.99	54.36	55.22	52.34	53.61	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
59.78	59.95	60.66	60.12	62.66	63.90	63.26	62.34	59.11	59.73	58.68	58.75

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.30	3.39	3.89	3.88	4.87	4.60	3.78	4.76	2.52	2.19	3.37	2.99

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
60.85	64.12	61.01	66.08	61.85	58.62	58.90	54.53

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
4.65	1.77	1.68	2.86	2.65	1.21	1.01	1.40

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 4.11

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 69.79

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 93.75

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.79

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 60.78

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.29

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.58

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B35. Analysis of density distribution, Test 60

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	52.66	50.57	54.62	56.65	67.24	66.90	67.78	65.83	55.40	57.14	54.39	52.55	I
II	57.01	55.23	54.47	55.26	61.07	59.70	62.02	63.18	61.12	60.64	56.33	56.93	II
S III	62.10	60.76	61.23	58.26	63.16	65.18	66.23	65.67	62.82	63.44	56.80	59.52	III
L IV	62.93	63.53	64.69	65.04	72.21	72.64	72.64	72.64	66.21	64.85	64.46	65.07	IV
A V	60.81	59.53	61.28	59.77	65.90	67.47	67.13	63.72	58.04	60.44	55.80	56.86	V
B VI	60.57	60.92	61.86	58.92	64.55	66.22	65.93	64.18	58.61	60.26	54.63	55.69	VI
VII	55.79	56.61	57.44	56.23	60.12	59.85	58.66	58.26	53.71	53.57	53.28	53.44	VII
VIII	56.52	56.00	57.89	57.47	63.78	64.51	61.86	61.37	55.02	55.72	55.48	54.12	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
58.55	57.89	59.18	58.45	64.75	65.31	65.28	64.36	58.85	59.51	56.40	56.77

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.35	3.84	3.42	2.85	3.56	3.93	4.05	3.88	4.02	3.57	3.23	3.77

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
58.47	58.58	62.10	67.24	61.40	61.03	56.41	58.31

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
6.24	2.90	2.81	3.82	3.72	3.59	2.41	3.45

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 4.91

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 65.63

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.85

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 60.24

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.41

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.67

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B36. Analysis of density distribution, Test 61

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	36.55	39.34	36.92	36.39	35.65	37.38	38.23	35.29	36.57	38.12	35.40	36.22	I
II	40.89	40.64	42.86	41.00	40.65	42.03	41.30	40.35	42.08	41.03	40.55	40.77	II
S III	41.85	42.02	41.89	41.99	40.15	40.74	40.96	39.72	43.07	42.43	[illegible]	41.59	III
L IV	42.74	42.70	42.42	42.77	39.15	39.49	40.55	38.10	45.37	42.54	43.97	41.71	IV
A V	44.15	43.93	44.46	43.01	40.53	39.63	40.23	40.27	44.77	[illegible]	[illegible]	44.04	V
B VI	43.59	43.27	43.86	43.13	40.48	39.85	39.98	38.27	42.84	43.53	41.72	41.94	VI
VII	38.80	38.07	39.49	43.05	35.89	35.58	35.46	35.40	39.87	41.92	39.97	39.91	VII
VIII	38.03	39.62	39.18	40.59	35.40	35.45	36.92	35.65	39.25	39.97	39.70	39.48	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
40.83	40.95	41.39	41.49	38.61	38.78	39.20	37.88	41.83	41.68	41.08	40.35

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.59	2.21	2.43	2.13	2.11	2.24	1.97	2.04	2.84	1.78	2.67	2.10

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
36.24	41.18	41.70	41.79	42.62	41.96	38.54	38.09

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
0.97	0.73	1.12	2.01	1.80	1.76	2.46	1.73

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.63

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 100.00

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 26.03

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 40.39

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.33

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.18

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B37. Analysis of density distribution, Test 62

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top

SLAB	1	2	3	4	5	6	7	8	9	10	11	12	
I	[illegible]	37.41	[illegible]	[illegible]	[illegible]	36.12	[illegible]	36.69	[illegible]	[illegible]	[illegible]	[illegible]	I
II	[illegible]	[illegible]	37.00	36.87	[illegible]	[illegible]	35.49	36.47	[illegible]	[illegible]	[illegible]	[illegible]	II
III	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	36.21	[illegible]	[illegible]	[illegible]	[illegible]	III
IV	[illegible]	[illegible]	40.72	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	39.14	[illegible]	IV
V	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	41.13	V
VI	[illegible]	[illegible]	[illegible]	41.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	VI
VII	[illegible]	[illegible]	41.07	[illegible]	[illegible]	[illegible]	[illegible]	34.20	[illegible]	[illegible]	[illegible]	[illegible]	VII
VIII	[illegible]	[illegible]	39.80	38.10	34.89	[illegible]	[illegible]	35.12	[illegible]	[illegible]	[illegible]	[illegible]	VIII

bottom

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
[illegible]	[illegible]	39.55	38.48	36.09	[illegible]	36.11	36.04	[illegible]	[illegible]	38.28	[illegible]

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
[illegible]	1.91	2.36	2.31	0.61	[illegible]	[illegible]	[illegible]	1.93	[illegible]	2.19	[illegible]

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
36.42	36.57	37.46	39.21	39.53	39.92	38.42	37.31

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
0.70	0.66	1.58	2.28	2.54	2.47	2.57	1.72

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.34

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 61.46

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 100.00

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 26.2[illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 38.26

MOMENT COEFFICIENT OF SKEWNESS, A3 = [illegible].48

MOMENT COEFFICIENT OF KURTOSIS A4 = 1.7[illegible]

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into elements labeled 1, 2, ... 12

Figure B38. Analysis of density distribution, Test 63

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top		COLUMN											
	1	2	3	4	5	6	7	8	9	10	11	12	
I	35.87	37.87	34.41	34.53	35.65	35.00	34.13	33.08	34.09	35.90	34.62	34.91	I
II	40.47	41.36	39.13	37.42	36.14	36.89	36.37	35.54	35.52	37.58	36.62	36.43	II
S III	42.33	44.14	41.57	36.31	35.90	37.30	36.41	35.99	36.97	39.82	38.46	39.80	III
L IV	42.73	45.37	42.90	39.08	37.48	37.74	37.19	37.73	43.04	41.37	39.55	43.34	IV
A V	41.22	42.02	43.93	41.47	37.37	36.93	35.59	36.52	43.60	41.19	40.58	43.26	V
B VI	40.82	43.15	44.10	42.68	37.68	38.28	36.36	37.82	42.04	39.83	40.55	43.84	VI
VII	39.30	44.01	42.80	41.36	36.49	36.47	35.90	36.35	41.30	39.34	39.84	42.10	VII
VIII	37.12	38.85	36.76	36.72	35.68	34.88	34.78	35.28	37.76	37.66	35.76	39.03	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
39.98	42.10	40.70	38.70	36.30	36.69	35.84	36.14	39.29	39.09	38.25	40.34

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.27	2.46	3.35	2.72	1.23	1.13	0.92	1.21	3.42	1.78	2.15	3.15

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
34.90	37.46	38.75	40.63	40.31	40.60	39.60	36.69

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
1.12	1.81	2.66	2.71	2.82	2.52	2.68	1.39

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.02

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 98.96

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 26.20

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 38.84

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.38

MOMENT COEFFICIENT OF KURTOSIS A4 - 1.97

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B39. Analysis of density distribution, Test 64

ANALYSIS OF RELATIVE DENSITY DISTRIBUTION

COLUMN

top

SLAB	1	2	3	4	5	6	7	8	9	10	11	12	
I	32.67	32.79	32.50	33.78	33.80	34.19	34.08	33.72	32.38	33.19	32.58	32.22	I
II	37.44	37.60	37.31	36.88	38.29	37.95	37.14	38.56	38.17	37.56	35.84	37.92	II
III	38.43	38.07	39.36	40.32	38.20	40.75	40.87	39.36	40.68	39.66	39.60	39.98	III
IV	39.36	38.91	38.50	39.16	35.41	35.10	35.39	35.22	37.98	37.95	38.75	38.62	IV
V	40.65	39.25	38.75	38.89	35.45	35.61	34.69	34.46	37.29	38.06	38.77	38.54	V
VI	40.61	38.42	38.93	37.69	36.12	35.46	35.43	34.67	37.68	39.76	39.84	39.10	VI
VII	42.03	40.44	39.94	38.32	38.94	38.25	38.73	37.24	38.43	39.53	38.76	38.05	VII
VIII	35.29	35.62	35.97	34.04	32.68	33.80	33.18	32.15	34.46	34.32	36.15	34.10	VIII

bottom

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
39.31	37.64	37.65	37.38	36.10	36.39	36.19	35.67	37.13	37.38	37.41	37.32

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.90	2.25	2.26	2.22	2.08	2.23	2.41	2.33	2.40	2.22	2.23	2.52

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
33.16	37.56	39.61	37.53	37.54	37.64	39.04	34.31

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
0.69	0.70	0.94	1.64	1.92	1.75	1.22	1.22

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.46

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 64.58

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 98.96

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 26.37

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 37.30

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.38

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.08

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B40. Analysis of density distribution, Test 66

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	30.91	30.18	31.73	33.21	37.93	34.21	33.24	37.65	29.79	31.35	30.92	31.23	I
II	32.72	31.99	33.85	33.76	39.37	38.32	38.57	39.97	35.67	35.48	31.11	32.30	II
S III	36.15	36.64	37.98	37.69	36.79	36.44	36.54	36.01	36.82	37.73	35.70	35.69	III
L IV	[illegible]	39.75	39.95	39.07	37.12	35.98	36.54	36.97	39.00	40.04	39.93	39.91	IV
A V	40.17	40.94	40.09	40.12	36.34	35.47	35.66	35.79	39.49	39.29	40.11	39.11	V
B VI	39.35	40.91	39.23	39.10	36.99	36.70	36.47	36.19	38.90	38.29	39.04	38.62	VI
VII	38.96	39.51	38.44	37.76	37.87	37.51	37.30	37.82	38.70	37.19	37.56	38.94	VII
VIII	35.19	35.37	36.98	36.45	35.15	35.42	34.80	34.58	36.89	34.79	36.43	38.25	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
36.57	36.91	37.27	37.15	37.19	36.26	36.14	36.87	37.01	36.77	36.36	36.74

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
3.20	3.86	2.81	2.36	1.16	1.21	1.50	1.53	3.05	2.63	3.42	3.10

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
32.70	35.26	36.67	38.68	38.55	38.32	38.12	35.86

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.60	2.99	0.73	1.49	2.00	1.37	0.71	1.08

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 2.66

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 68.75

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 92.71

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 26.42

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 36.85

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.77

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.95

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B41. Analysis of density distribution, Test 67

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	4.52	8.68	10.08	7.93	24.95	25.46	27.34	26.34	5.68	5.77	6.74	6.54	I
II	4.69	12.31	8.78	11.51	26.39	24.32	24.09	25.46	9.69	9.46	10.17	11.08	II
S III	15.02	21.32	23.39	25.84	34.57	35.43	33.71	35.08	25.10	24.79	21.90	21.73	III
L IV	31.74	33.04	37.19	35.47	30.12	32.19	32.58	31.37	37.85	38.87	33.31	36.13	IV
A V	38.84	38.67	39.89	40.55	26.16	29.30	26.44	29.37	38.31	39.51	38.49	40.61	V
B VI	40.77	40.06	39.68	40.63	30.65	29.78	28.47	29.43	39.46	39.85	40.43	40.74	VI
VII	38.96	38.00	37.93	38.77	43.82	46.68	45.63	43.06	36.59	35.94	39.37	38.58	VII
VIII	36.72	35.15	38.01	39.42	48.07	47.67	48.21	48.76	38.15	38.92	34.92	35.44	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
26.41	28.40	29.37	30.02	33.09	33.85	33.31	33.61	28.85	29.14	28.17	28.79

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
14.72	11.72	12.54	12.58	8.03	8.36	8.41	7.75	12.98	13.28	12.64	12.86

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
13.34	14.83	26.49	34.16	35.51	36.62	40.28	40.79

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
9.09	7.47	6.38	2.72	5.56	5.01	3.43	5.40

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 11.81

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 73.96

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 94.79

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 27.11

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 30.59

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.77

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.58

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B42. Analysis of density distribution, Test 68

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	48.80	48.37	47.36	43.05	46.38	45.99	46.06	45.98	47.99	47.74	42.11	39.63	I
II	51.59	51.34	50.66	46.41	51.22	50.28	50.08	50.77	51.96	51.04	48.89	43.39	II
S III	52.10	52.09	52.09	49.80	50.84	50.37	49.32	50.30	52.60	51.25	51.43	46.35	III
L IV	48.49	48.53	48.26	47.79	49.02	49.20	49.09	49.34	48.24	48.78	47.70	46.53	IV
A V	53.97	53.58	53.42	54.38	48.71	48.35	48.24	48.63	55.40	55.05	53.31	54.31	V
B VI	54.51	53.86	54.75	53.81	47.32	47.81	48.17	48.25	55.85	53.62	53.25	54.54	VI
VII	53.30	53.27	54.81	52.72	49.79	50.71	51.15	50.14	53.78	53.16	52.18	53.94	VII
VIII	52.23	52.51	52.69	52.01	48.77	48.83	48.83	48.42	52.79	51.80	49.79	52.02	VIII
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
51.87	51.69	51.75	50.00	49.01	48.94	48.87	48.98	52.33	51.56	49.83	48.84

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
2.08	2.02	2.62	3.73	1.53	1.47	1.40	1.43	2.74	2.29	3.48	5.30

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
45.79	49.80	50.71	48.41	52.28	52.15	52.41	50.89

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII
2.68	2.40	1.64	0.76	2.75	3.08	1.55	1.70

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.06

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 70.83

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.83

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 24.94

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 50.36

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.63

MOMENT COEFFICIENT OF KURTOSIS A4 = 3.66

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... VIII
and each slab cut into segments labeled 1, 2, ... 12

Figure B43. Analysis of density distribution, Test 69/70

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	71.36	71.35	70.97	72.98	64.67	64.24	63.97	63.86	69.87	70.83	72.25	70.59	I
II	68.81	68.94	70.64	70.86	61.48	61.55	61.05	60.61	66.93	67.04	70.61	68.76	II
S III	70.12	71.09	71.03	70.91	61.90	62.12	61.00	60.31	67.77	68.74	69.33	71.67	III
L IV	67.95	68.36	69.58	68.89	61.16	61.67	60.80	59.90	66.85	66.37	68.30	67.35	IV
A V	69.03	68.69	69.76	71.59	63.78	63.23	64.23	62.79	67.28	68.19	68.77	67.16	V
B VI	68.52	67.80	68.99	68.49	63.27	63.06	63.85	63.39	67.22	67.93	68.11	67.75	VI
VII	67.54	67.23	68.38	68.89	64.13	63.41	63.88	64.35	67.27	67.96	68.39	67.15	VII
VIII	70.24	70.96	71.39	70.91	67.51	67.96	68.12	67.82	70.14	69.30	69.25	69.33	VIII
IX	70.20	70.77	70.51	70.08	66.81	67.44	67.97	67.16	70.05	69.99	70.26	70.04	IX
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
69.31	69.47	70.14	70.40	63.86	63.85	63.88	63.35	68.15	68.48	69.47	68.87

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.18	1.49	0.96	1.38	2.11	2.22	2.60	2.68	1.34	1.32	1.27	1.56

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII	IX
68.91	66.44	67.16	65.60	67.04	66.53	66.55	69.41	69.27

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII	IX
3.43	3.92	4.27	3.45	2.74	2.27	1.92	1.28	1.40

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.21

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 62.96

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 95.37

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.04

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 67.62

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.71

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.49

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... IX
and each slab cut into segments labeled 1, 2, ... 12

Figure B44. Analysis of density distribution, Test A

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	65.55	69.02	70.52	70.88	67.03	68.31	67.17	66.64	67.72	67.63	70.46	67.47	I
II	65.91	67.68	67.98	67.61	61.47	62.62	64.15	62.06	66.41	66.93	68.41	67.03	II
S III	64.51	65.83	65.33	66.09	60.19	59.10	58.24	59.05	63.35	63.33	66.70	65.41	III
L IV	65.27	65.92	67.06	66.36	59.87	59.61	59.17	58.16	62.26	62.57	66.10	64.43	IV
A V	64.20	65.16	66.61	65.12	59.36	59.03	58.04	58.77	63.28	62.61	65.66	65.81	V
B VI	65.12	66.83	67.30	68.12	60.04	59.62	59.59	59.80	62.35	62.28	66.63	65.12	VI
VII	66.36	67.23	68.18	66.53	61.44	60.88	60.44	60.88	65.62	64.90	66.76	67.07	VII
VIII	68.26	69.01	68.44	68.37	64.05	62.14	61.95	63.17	66.69	65.79	67.93	66.78	VIII
IX	70.82	70.44	70.12	69.51	65.22	65.44	66.23	65.52	67.98	68.40	70.36	69.40	IX
bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
66.22	67.46	67.95	67.62	62.07	61.86	61.67	61.56	65.07	64.94	67.67	66.50

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
1.97	1.65	1.54	1.71	2.56	3.01	3.24	2.86	2.15	2.23	1.67	1.41

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII	IX
68.20	65.69	63.09	63.06	62.80	63.57	64.69	66.05	68.29

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII	IX
1.61	2.36	2.98	3.07	3.03	3.17	2.79	2.48	2.06

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 3.35

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION = 67.59

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION = 97.22

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST = 23.31

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST = 65.21

MOMENT COEFFICIENT OF SKEWNESS, A3 = -0.45

MOMENT COEFFICIENT OF KURTOSIS A4 = 2.28

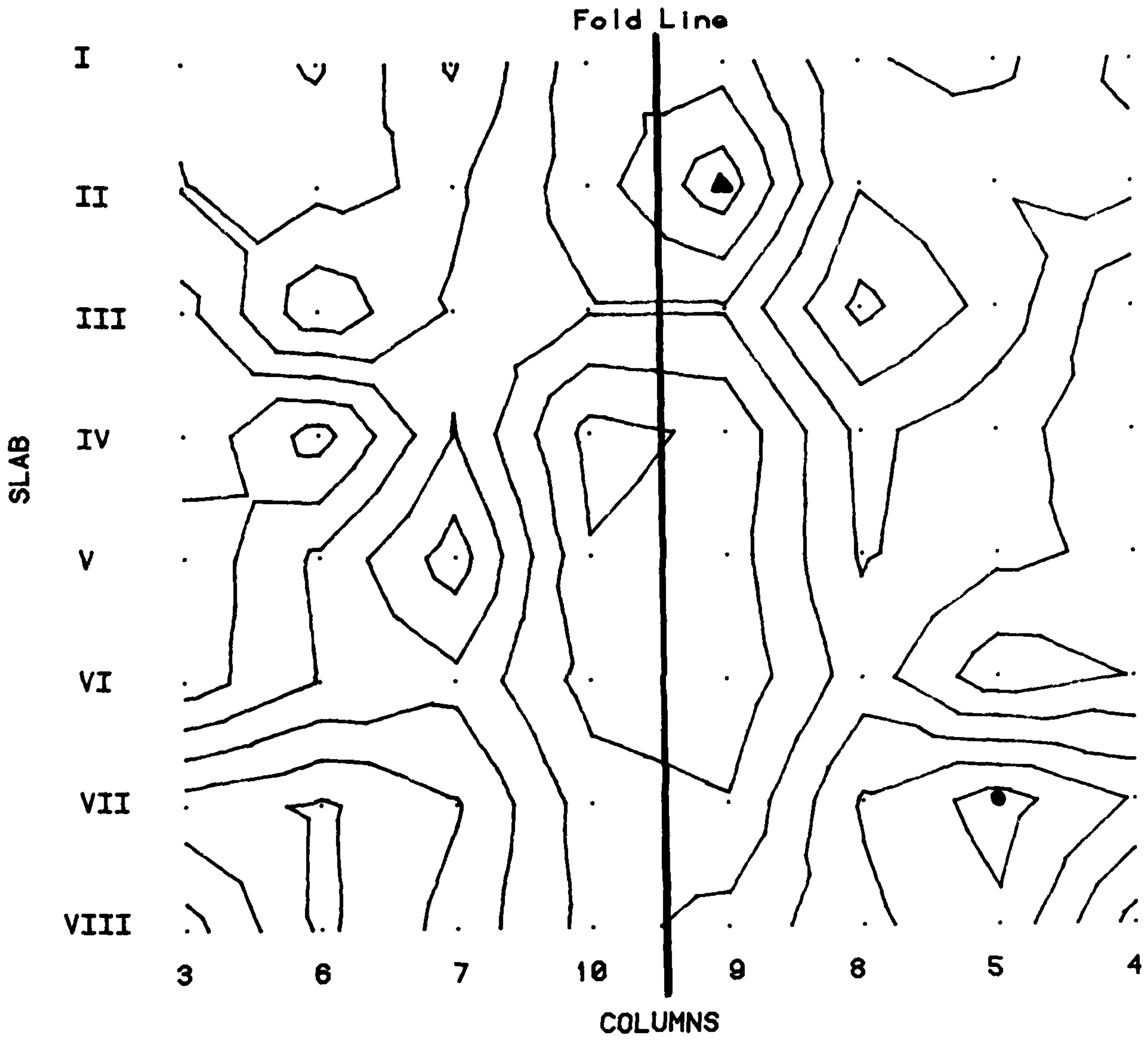
NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... IX
and each slab cut into segments labeled 1, 2, ... 12

Figure B45. Analysis of density distribution, Test B

APPENDIX C

DENSITY CONTOURS IN INDIVIDUAL TEST SPECIMENS

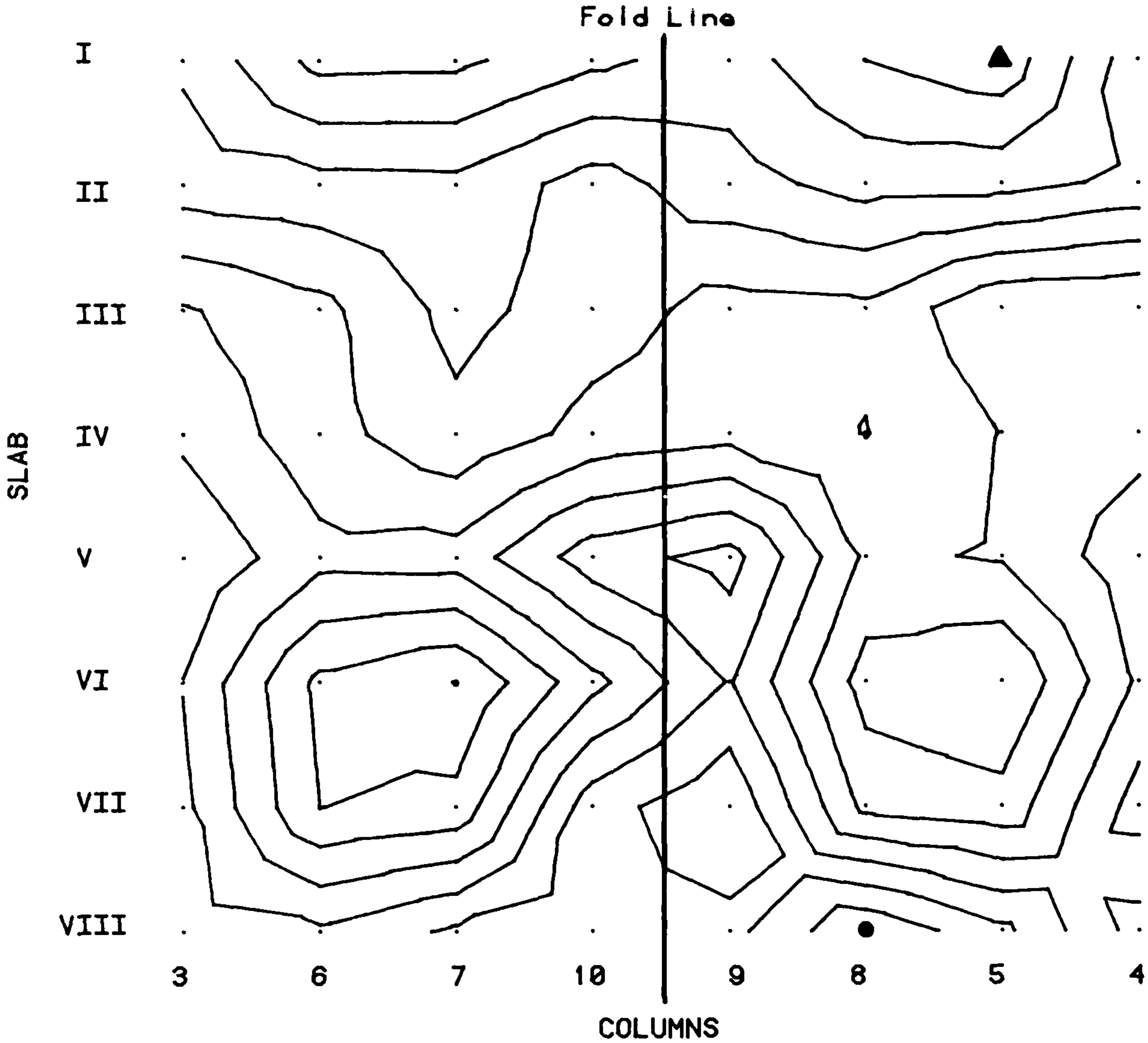


▲ Maximum Percent Relative Density, 60.62

● Minimum Percent Relative Density, 54.57

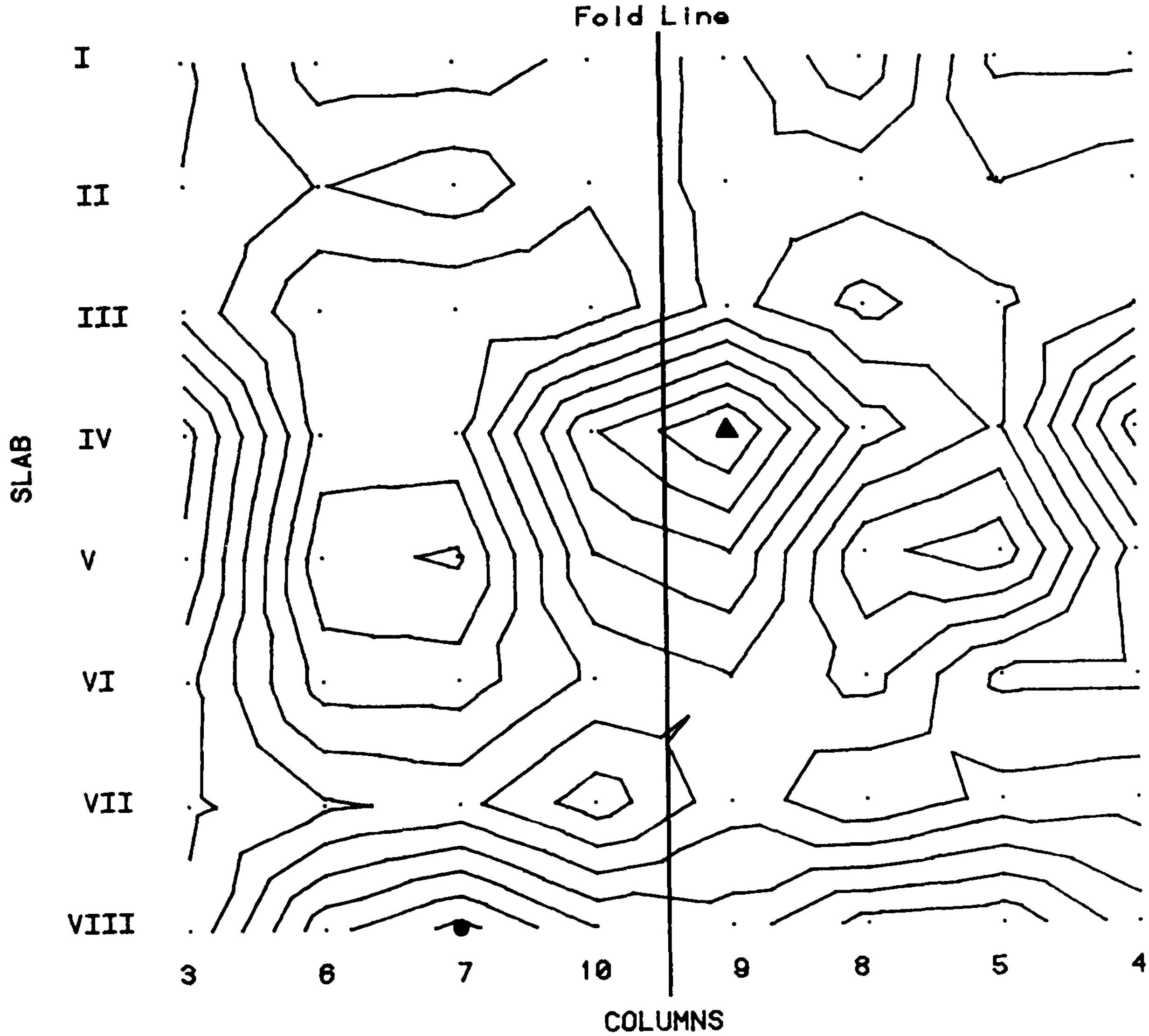
Contour line spacing is 1 percent relative density.

Fig.C1. Density contour, specimen no.10



▲ Maximum Percent Relative Density, 61.68
● Minimum Percent Relative Density, 51.12
Contour line spacing is 1 percent relative density.

Fig.C2. Density contour, specimen no.11

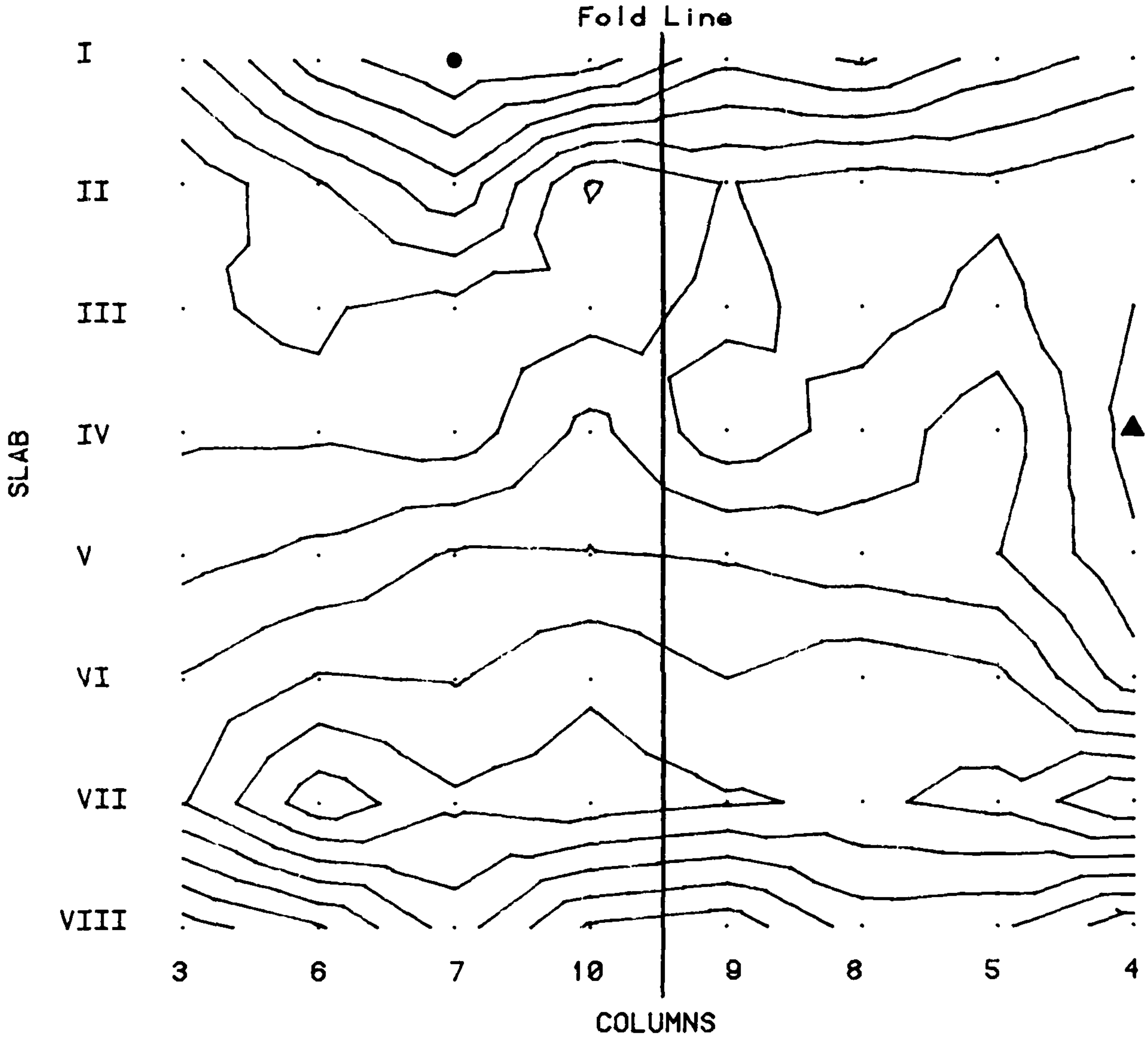


▲ Maximum Percent Relative Density, 66.09

● Minimum Percent Relative Density, 55.68

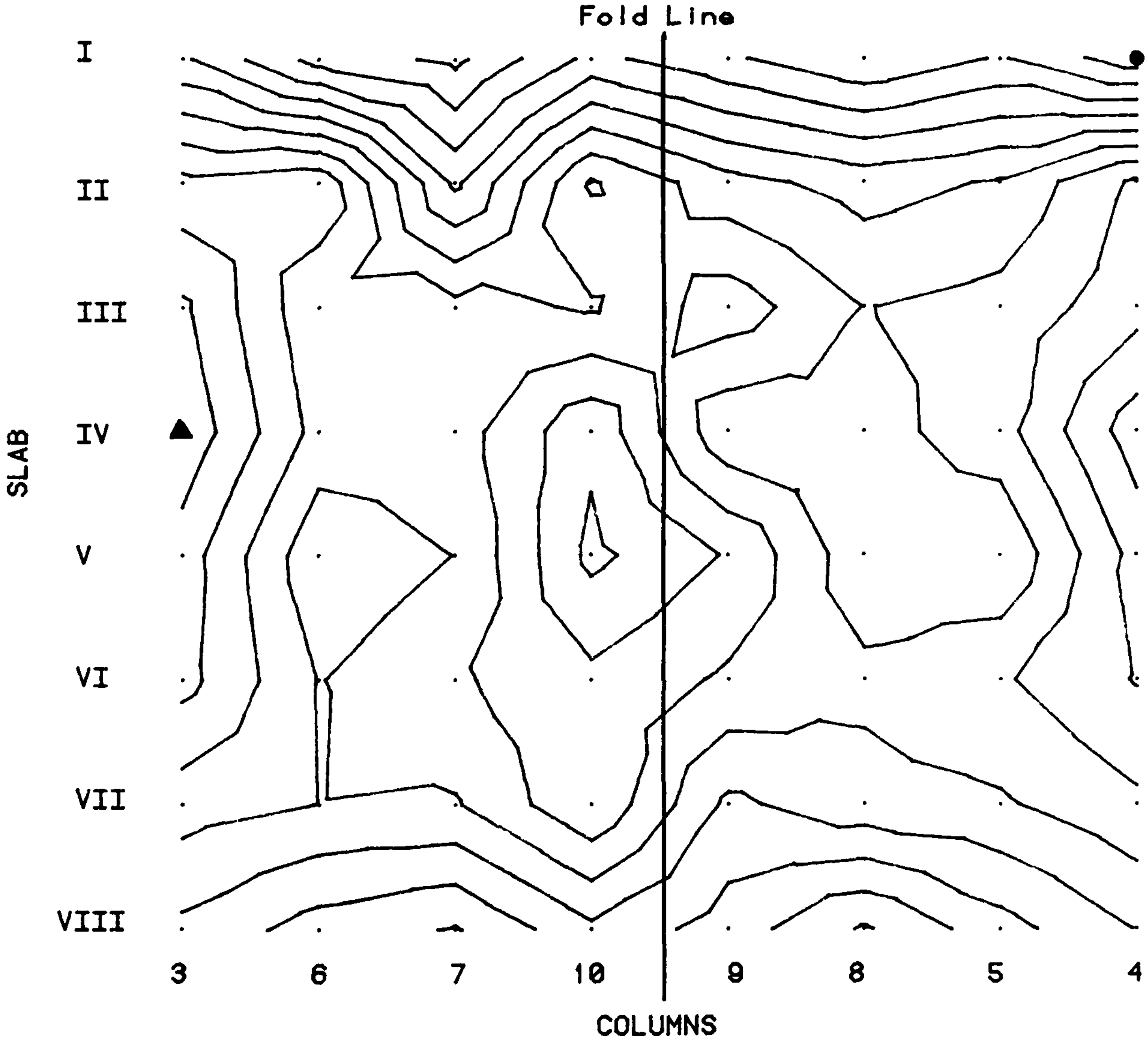
Contour line spacing is 1 percent relative density.

Fig.C3. Density contour, specimen no.12



▲ Maximum Percent Relative Density, 61.46
● Minimum Percent Relative Density, 54.05
Contour line spacing is 1 percent relative density.

Fig.C4. Density contour, specimen no.14

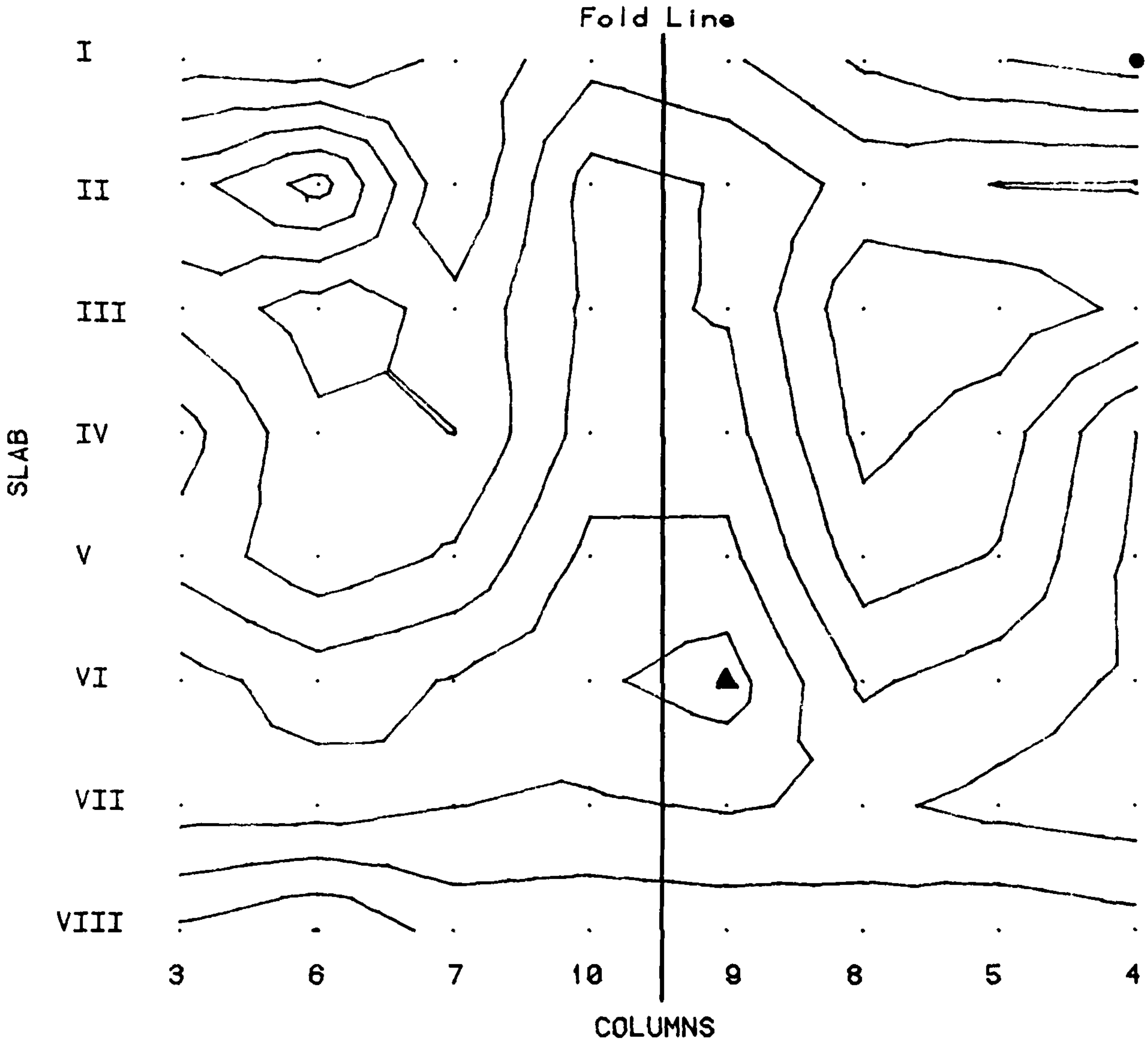


▲ Maximum Percent Relative Density, 65.75

● Minimum Percent Relative Density, 55.32

Contour line spacing is 1 percent relative density.

Fig.C5. Density contour, specimen no.15

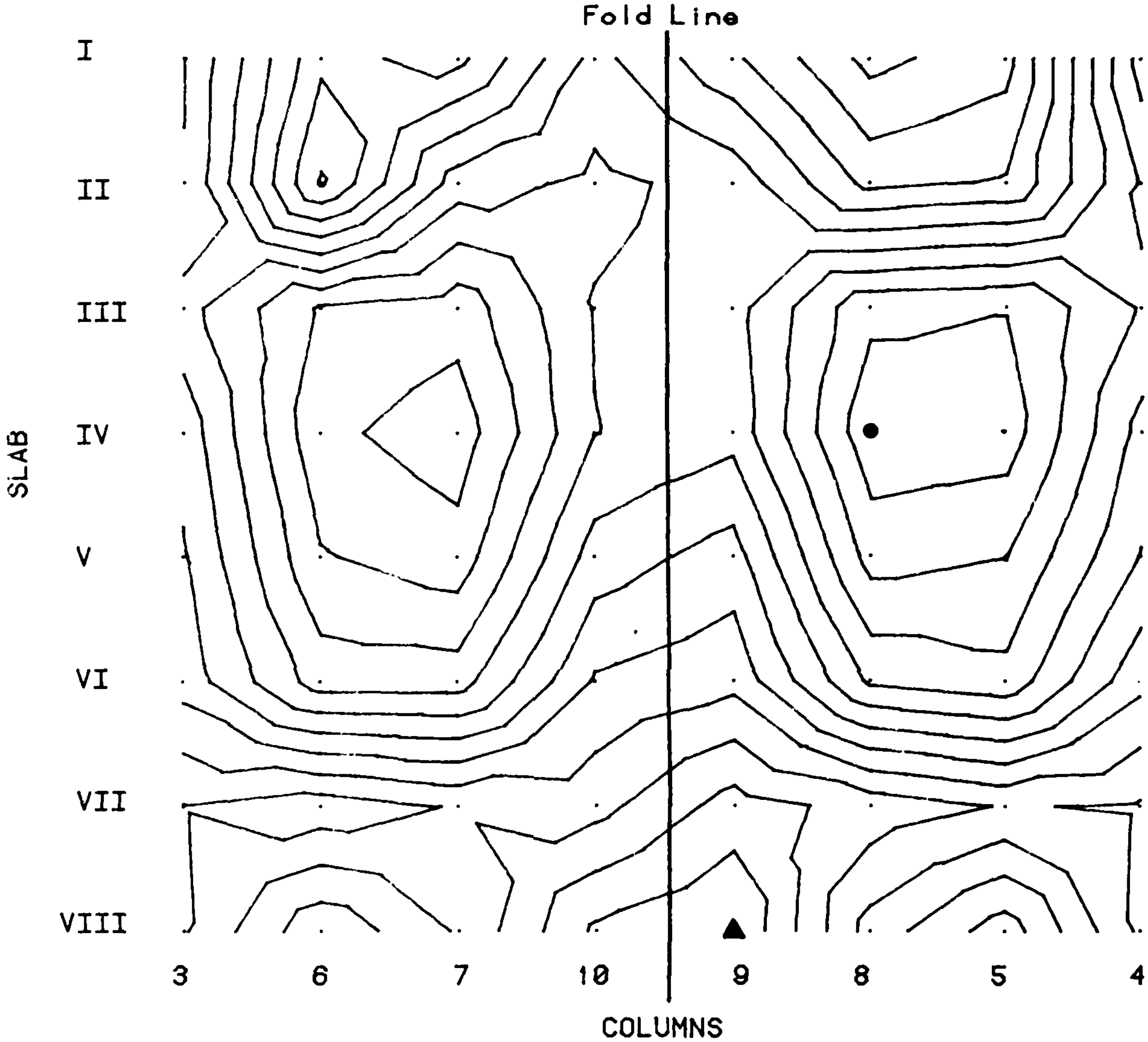


▲ Maximum Percent Relative Density, 59.46

● Minimum Percent Relative Density, 52.53

Contour line spacing is 1 percent relative density.

Fig.C6. Density contour, specimen no.16

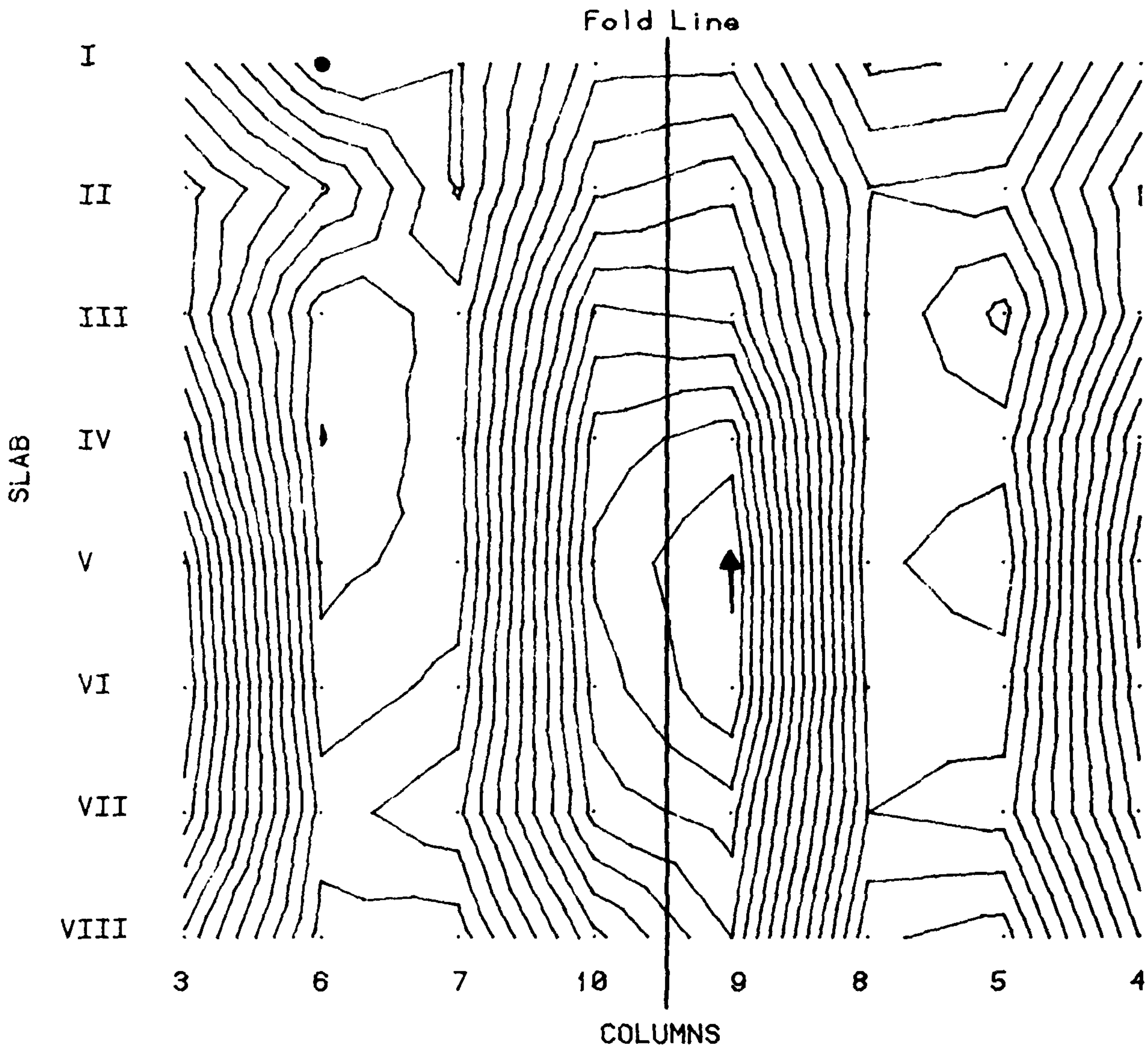


▲ Maximum Percent Relative Density, 64.97

● Minimum Percent Relative Density, 53.49

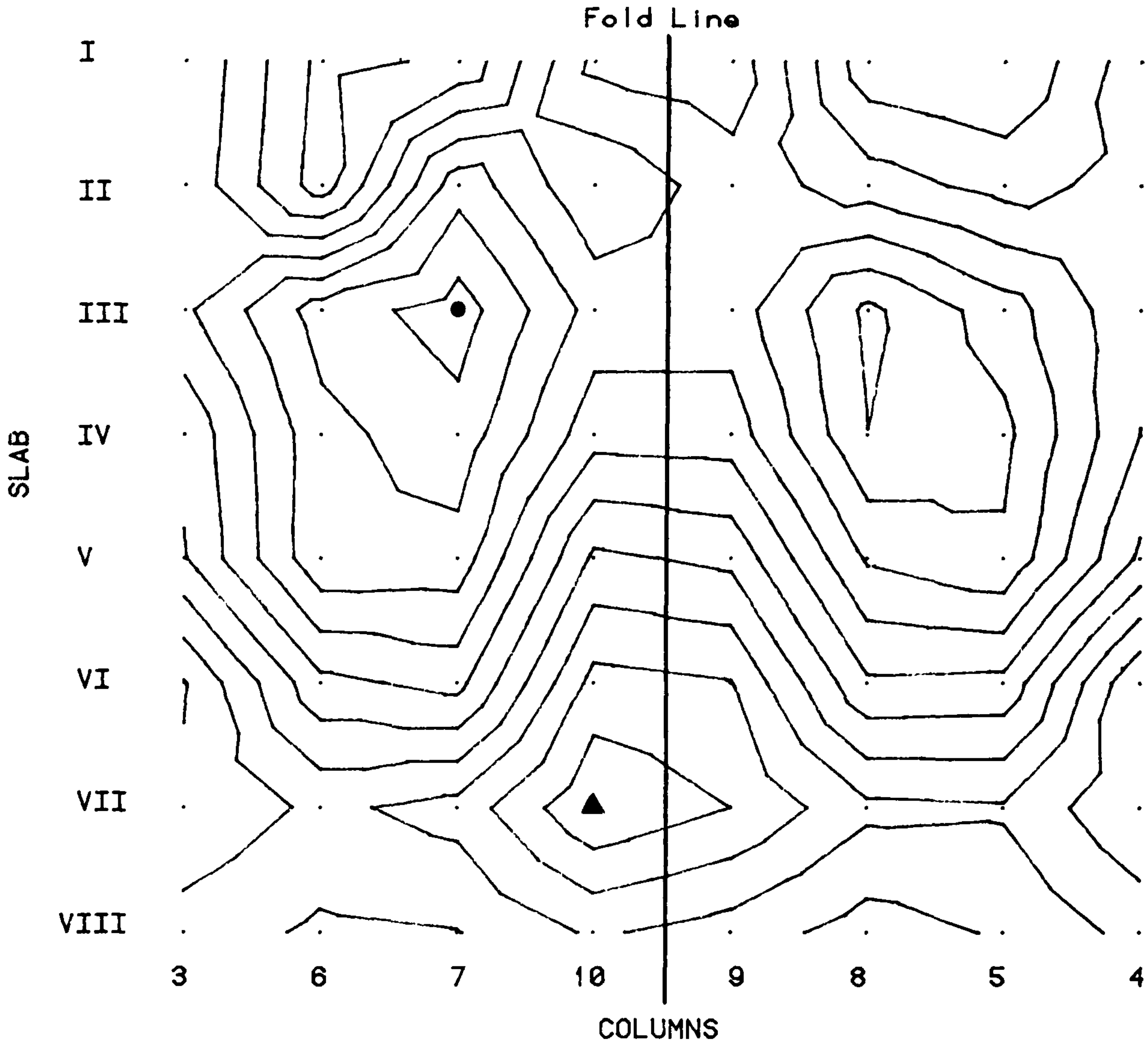
Contour line spacing is 1 percent relative density.

Fig. C7. Density contour, specimen no. 17



▲ Maximum Percent Relative Density, 70.05
● Minimum Percent Relative Density, 54.02
Contour line spacing is 1 percent relative density.

Fig. C8. Density contour, specimen no. 18

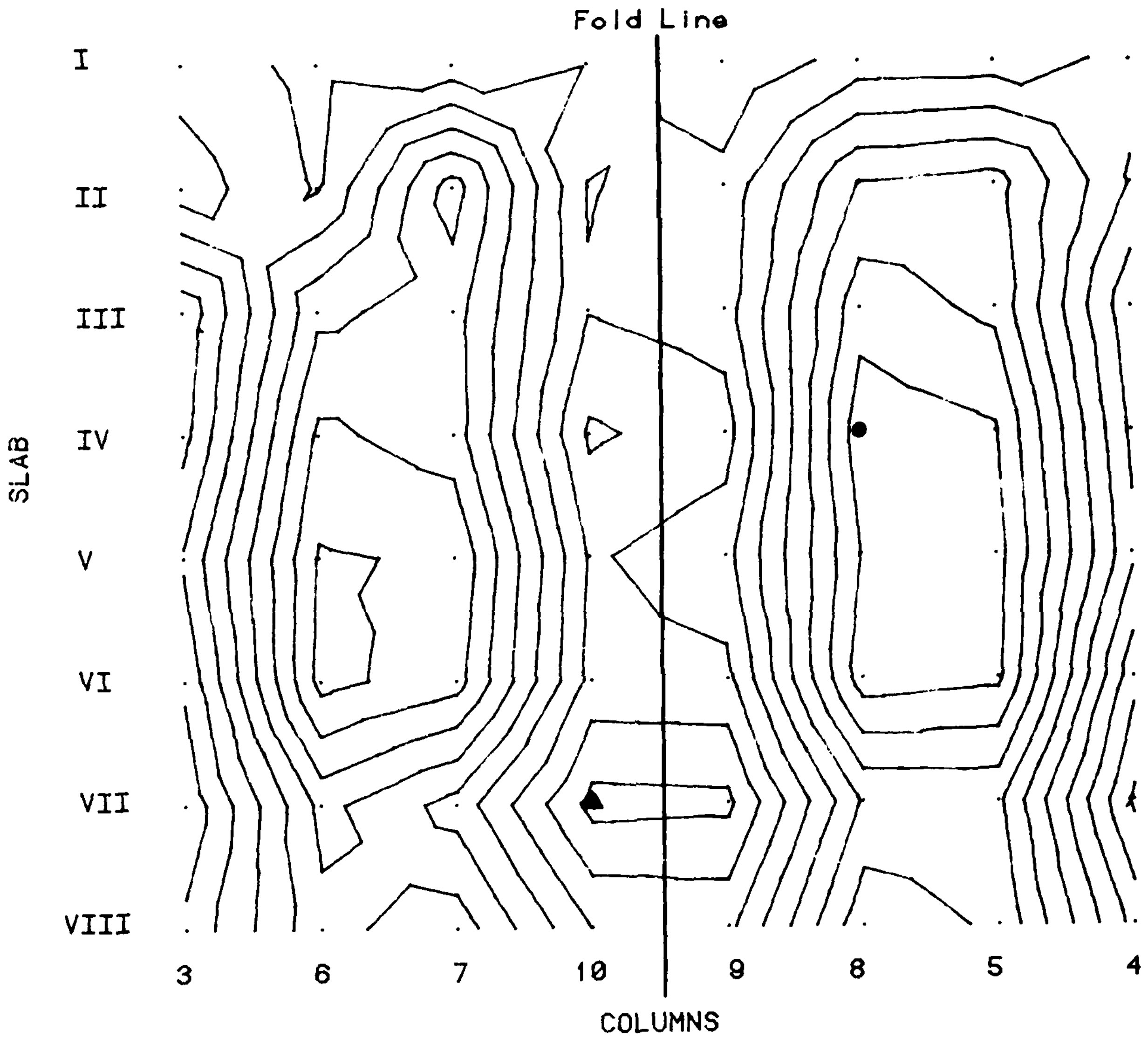


▲ Maximum Percent Relative Density, 63.91

● Minimum Percent Relative Density, 53.52

Contour line spacing is 1 percent relative density.

Fig.C9. Density contour, specimen no.19

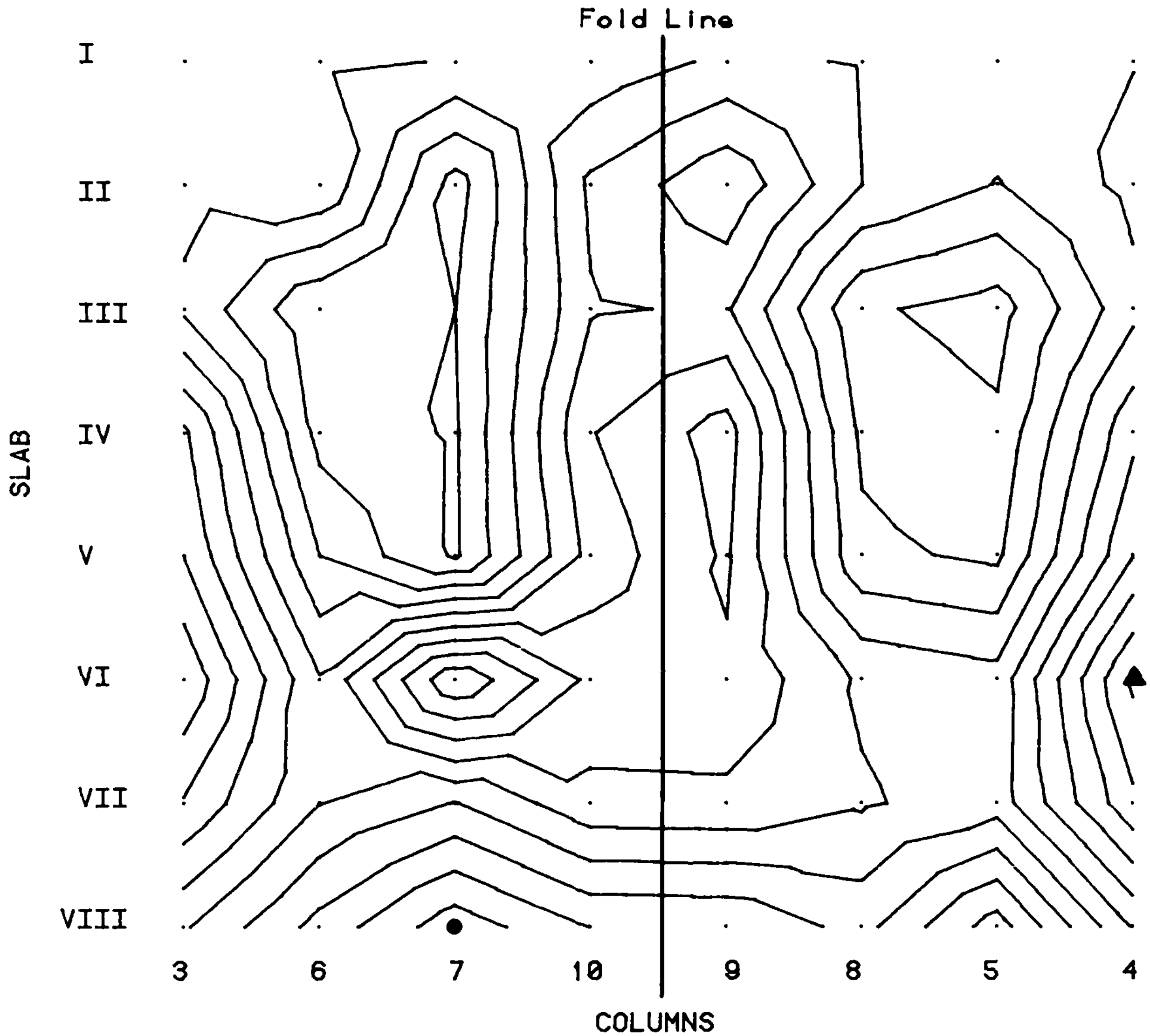


▲ Maximum Percent Relative Density, 56.33

● Minimum Percent Relative Density, 47.41

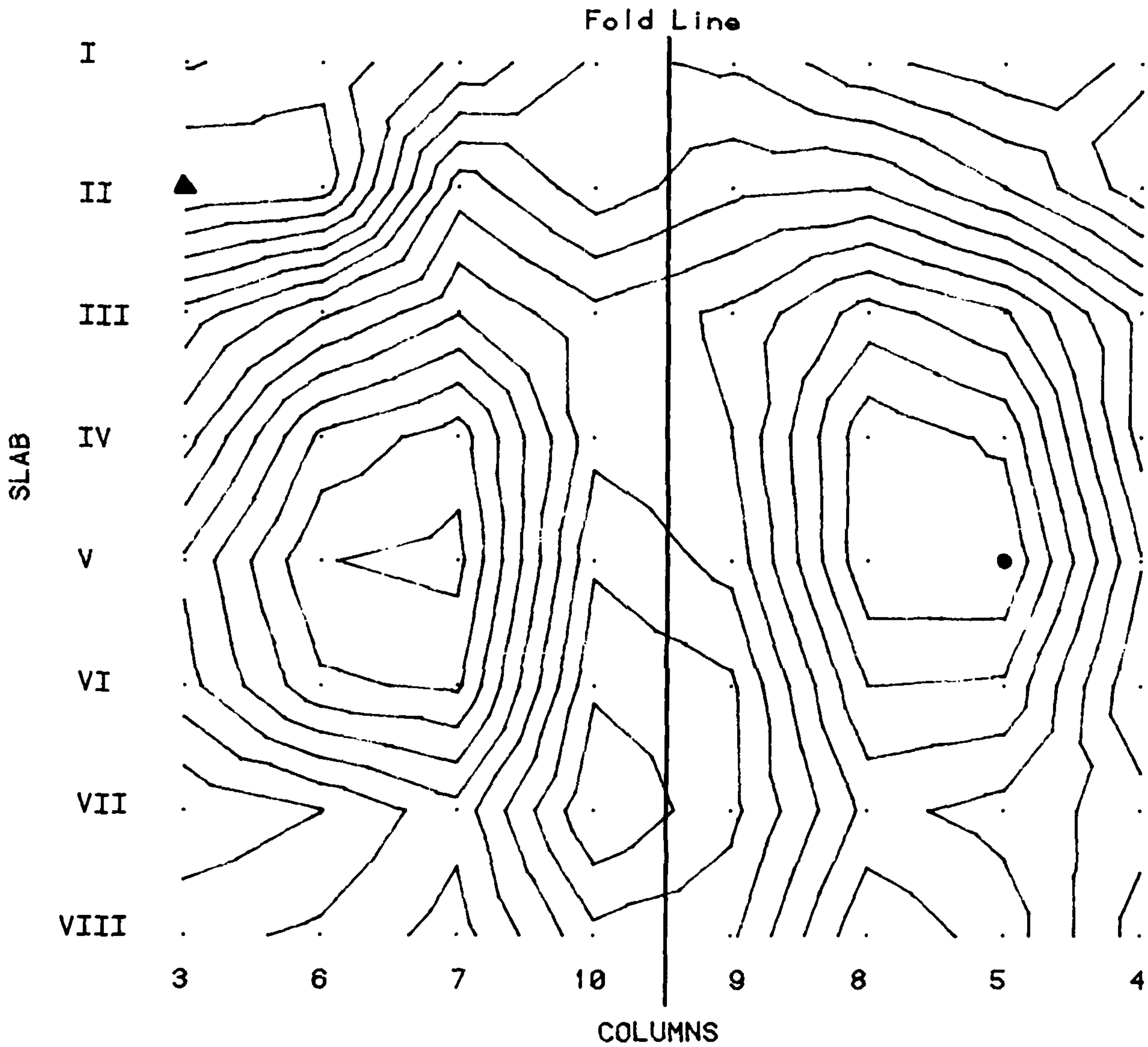
Contour line spacing is 1 percent relative density.

Fig.C10. Density contour, specimen no.20



▲ Maximum Percent Relative Density, 58.20
● Minimum Percent Relative Density, 48.38
Contour line spacing is 1 percent relative density.

Fig.C11. Density contour, specimen no.21

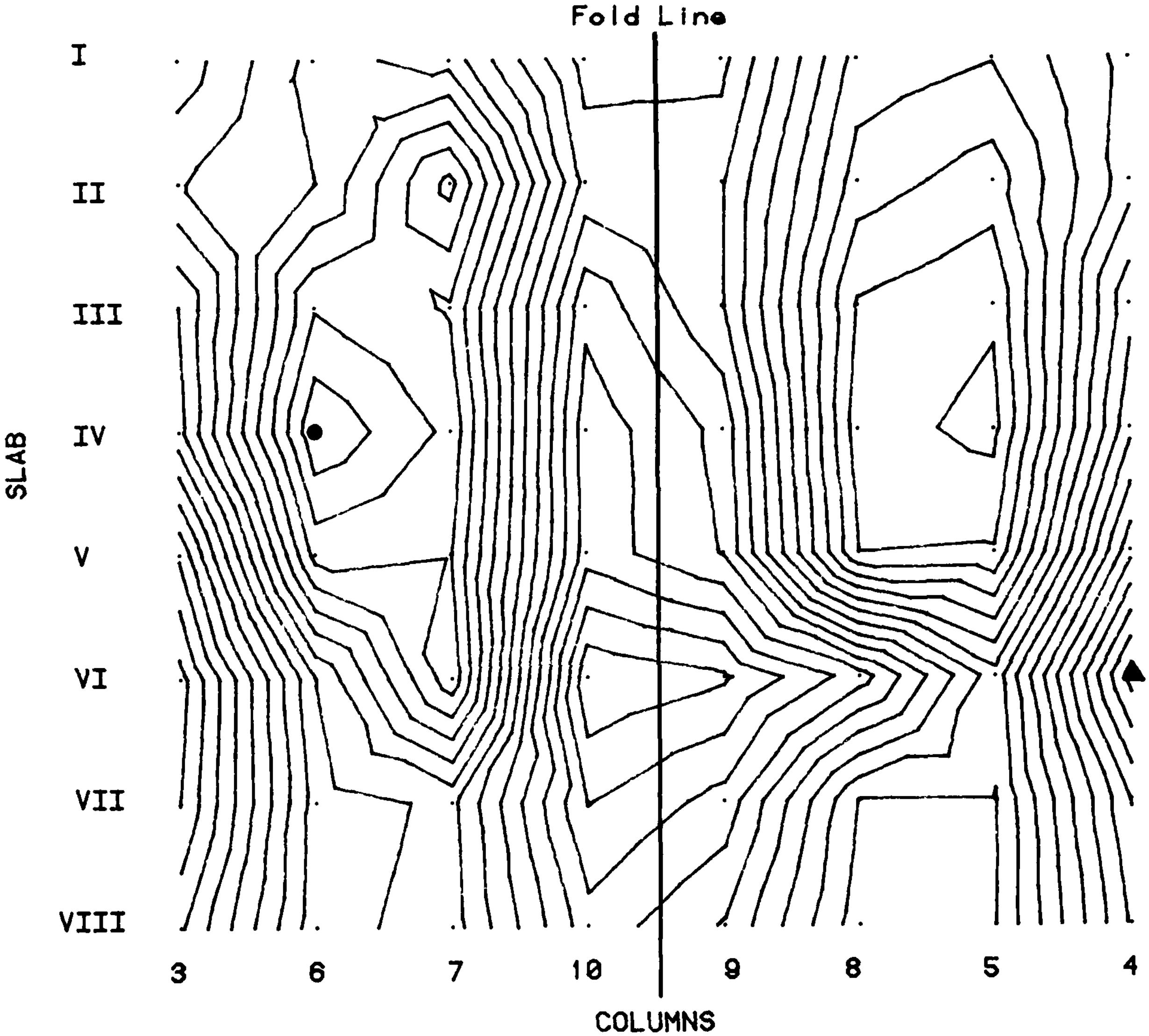


▲ Maximum Percent Relative Density, 58.00

● Minimum Percent Relative Density, 44.02

Contour line spacing is 1 percent relative density.

Fig.C12. Density contour, specimen no.22

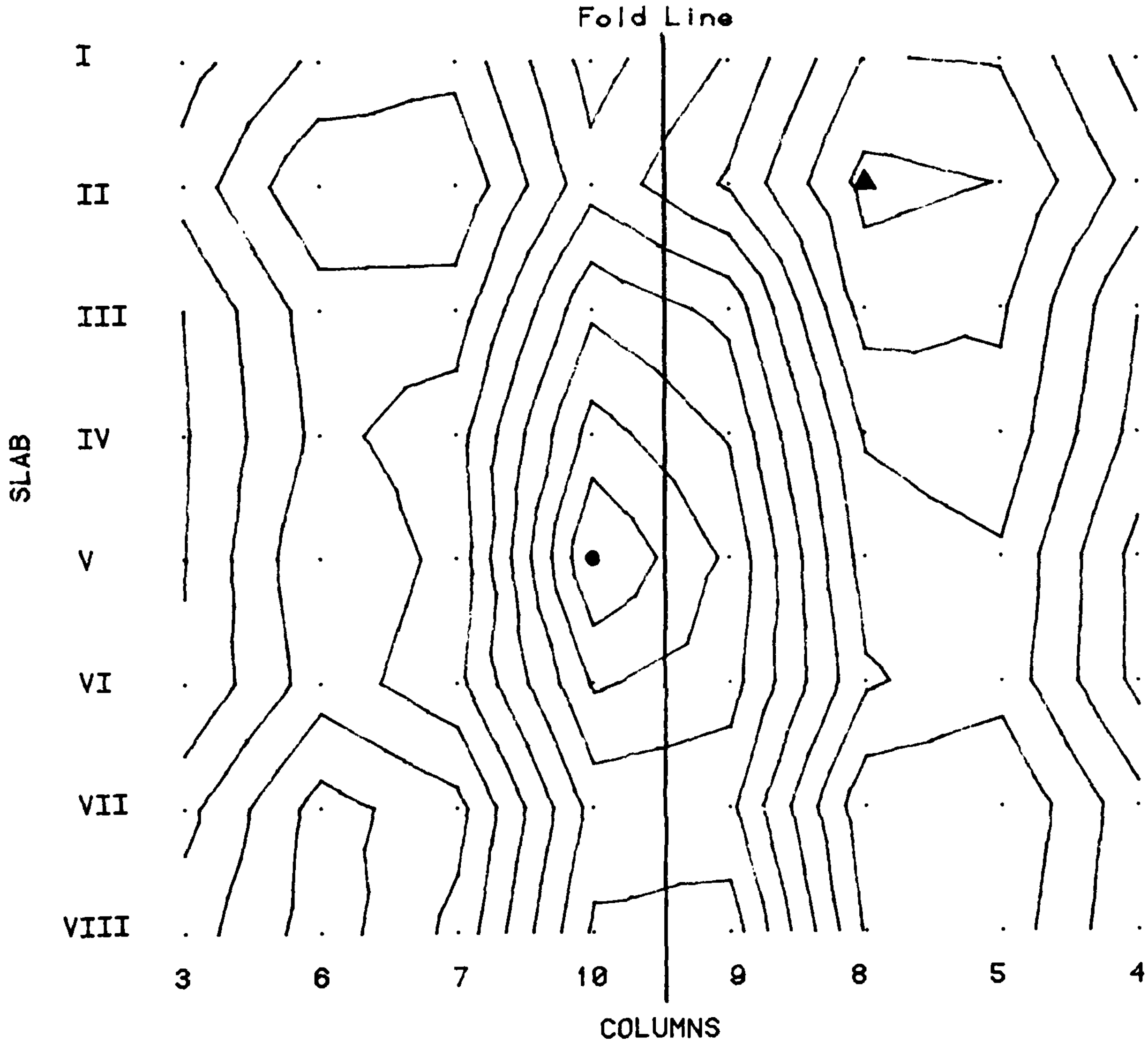


▲ Maximum Percent Relative Density, 64.46

● Minimum Percent Relative Density, 47.15

Contour line spacing is 1 percent relative density.

Fig.C13. Density contour, specimen no.23

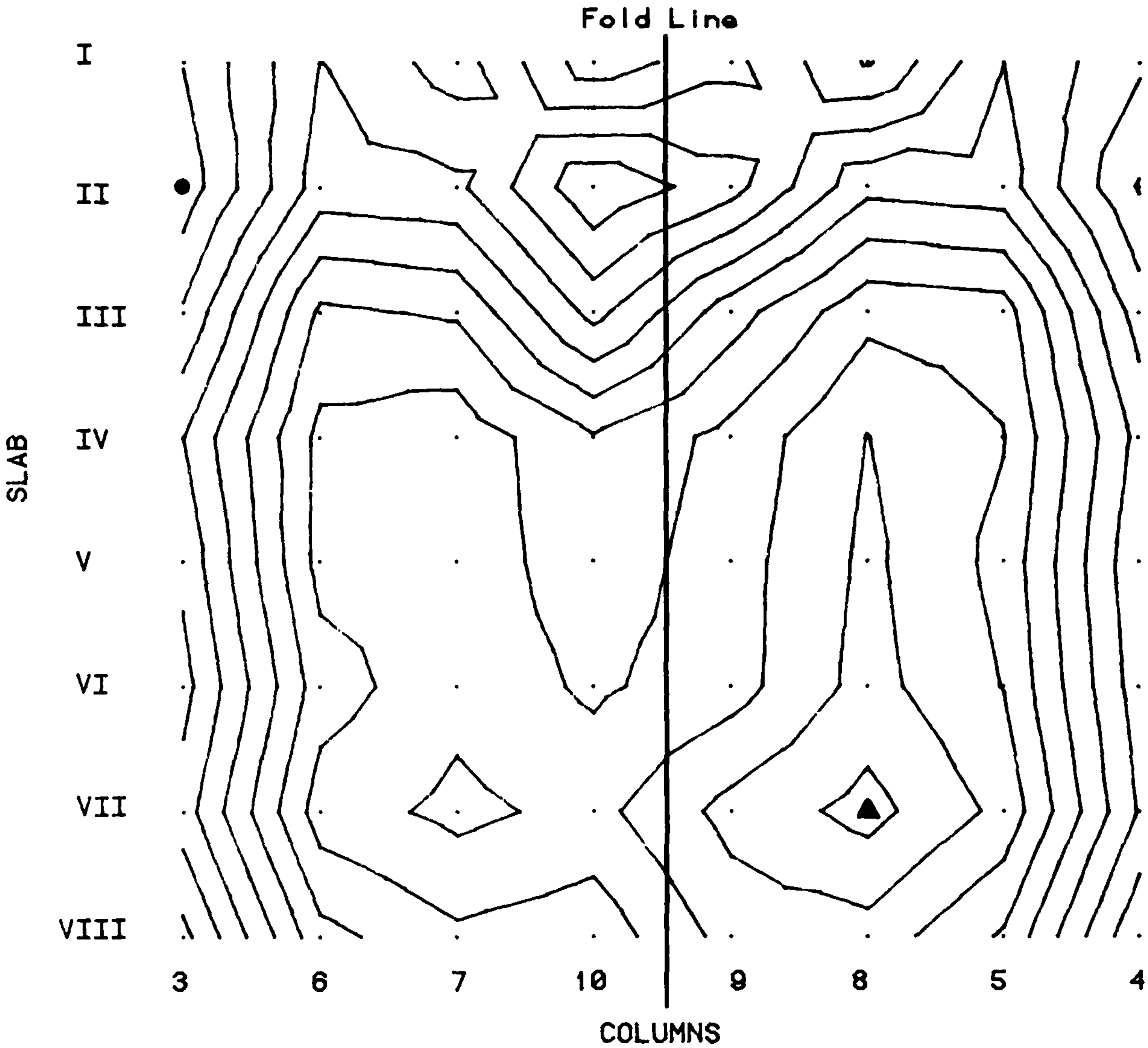


▲ Maximum Percent Relative Density, 80.31

● Minimum Percent Relative Density, 69.97

Contour line spacing is 1 percent relative density.

Fig.C14. Density contour, specimen no.38

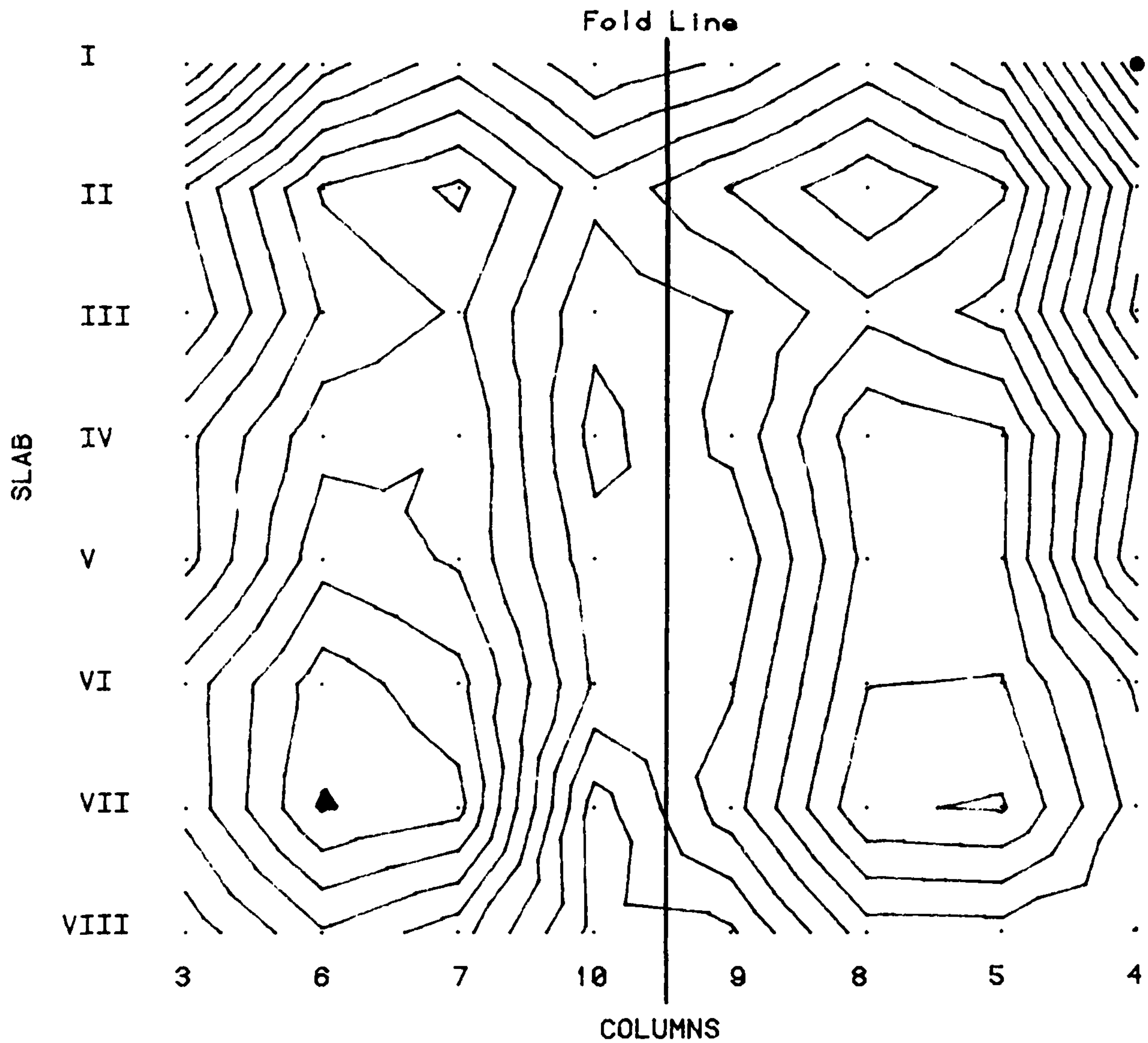


▲ Maximum Percent Relative Density, 80.35

● Minimum Percent Relative Density, 69.39

Contour line spacing is 1 percent relative density.

Fig.C15. Density contour, specimen no.39

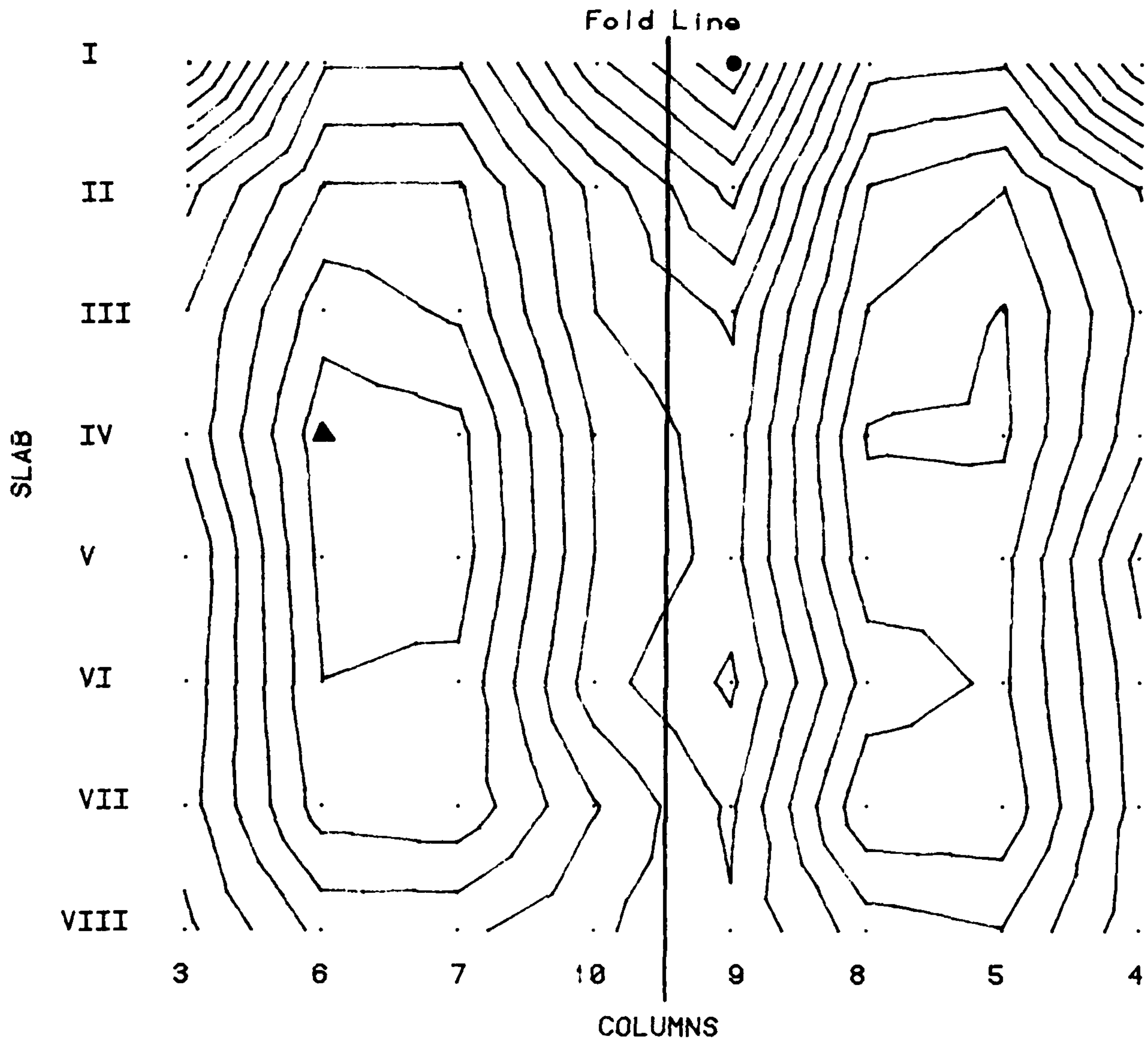


▲ Maximum Percent Relative Density, 74.07

● Minimum Percent Relative Density, 59.20

Contour line spacing is 1 percent relative density.

Fig.C16. Density contour, specimen no.40

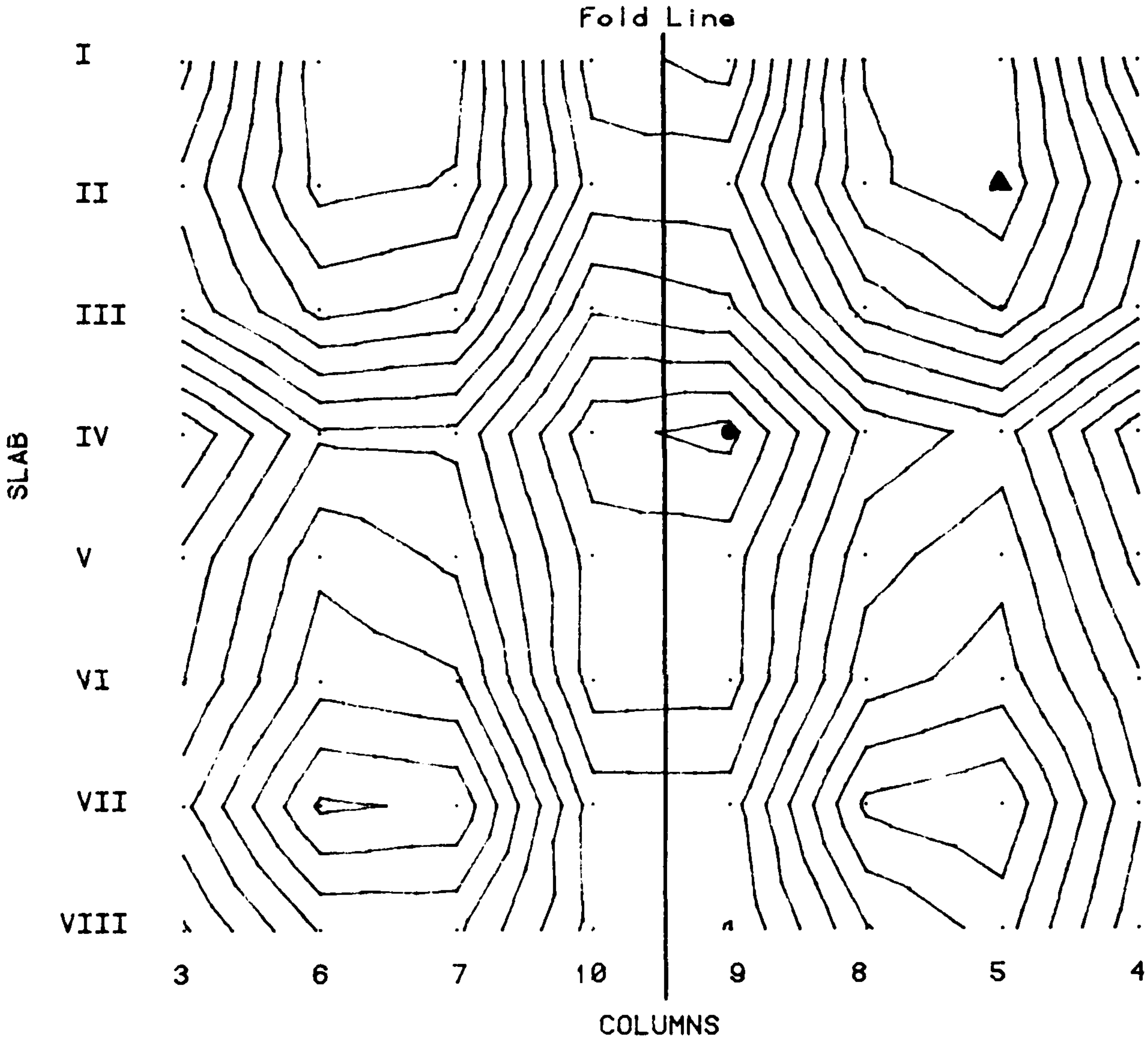


▲ Maximum Percent Relative Density, 76.62

● Minimum Percent Relative Density, 64.20

Contour line spacing is 1 percent relative density.

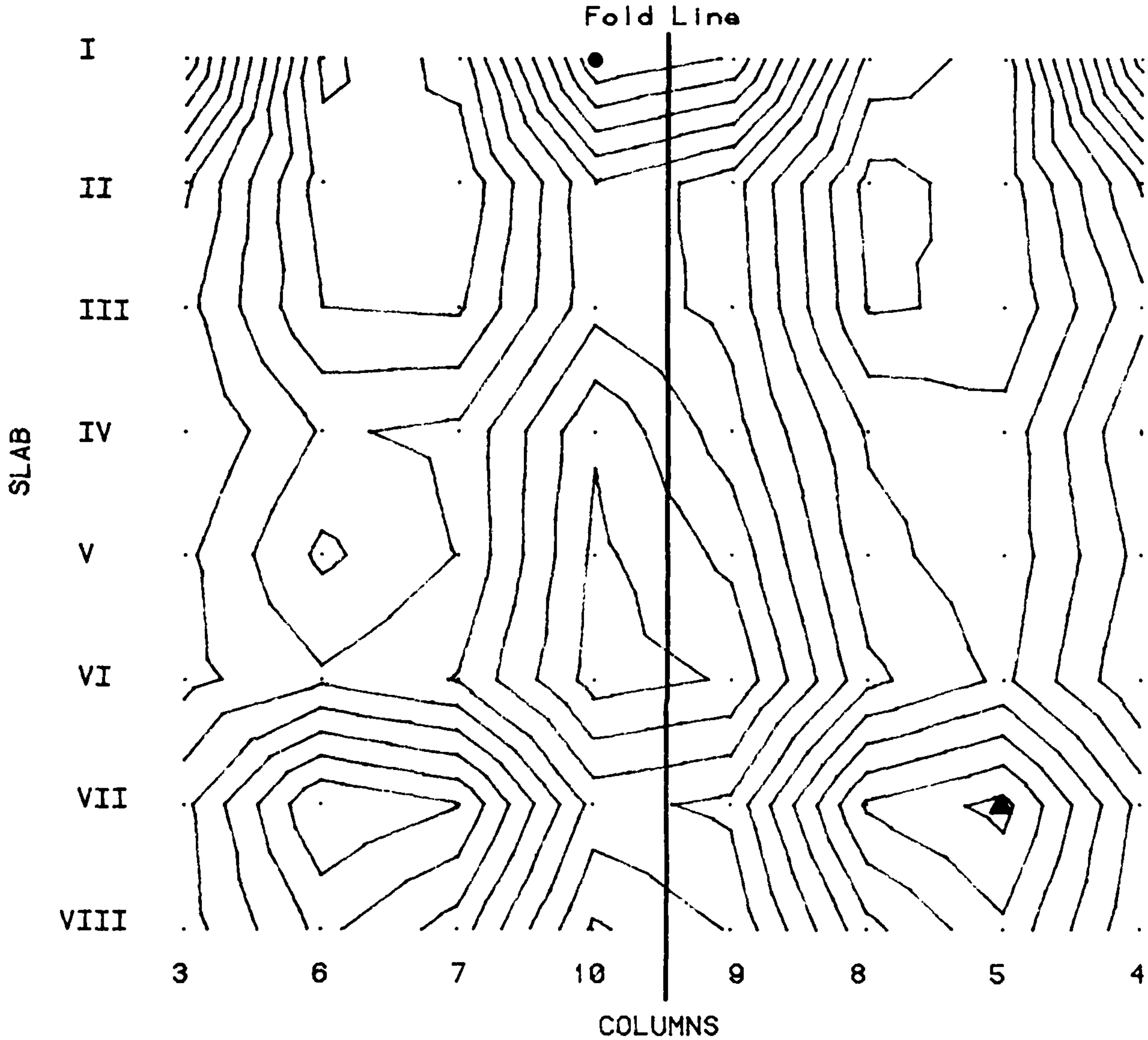
Fig.C17. Density contour, specimen no.41



▲ Maximum Percent Relative Density, 79.76
● Minimum Percent Relative Density, 67.68

Contour line spacing is 1 percent relative density.

Fig.C18. Density contour, specimen no.42

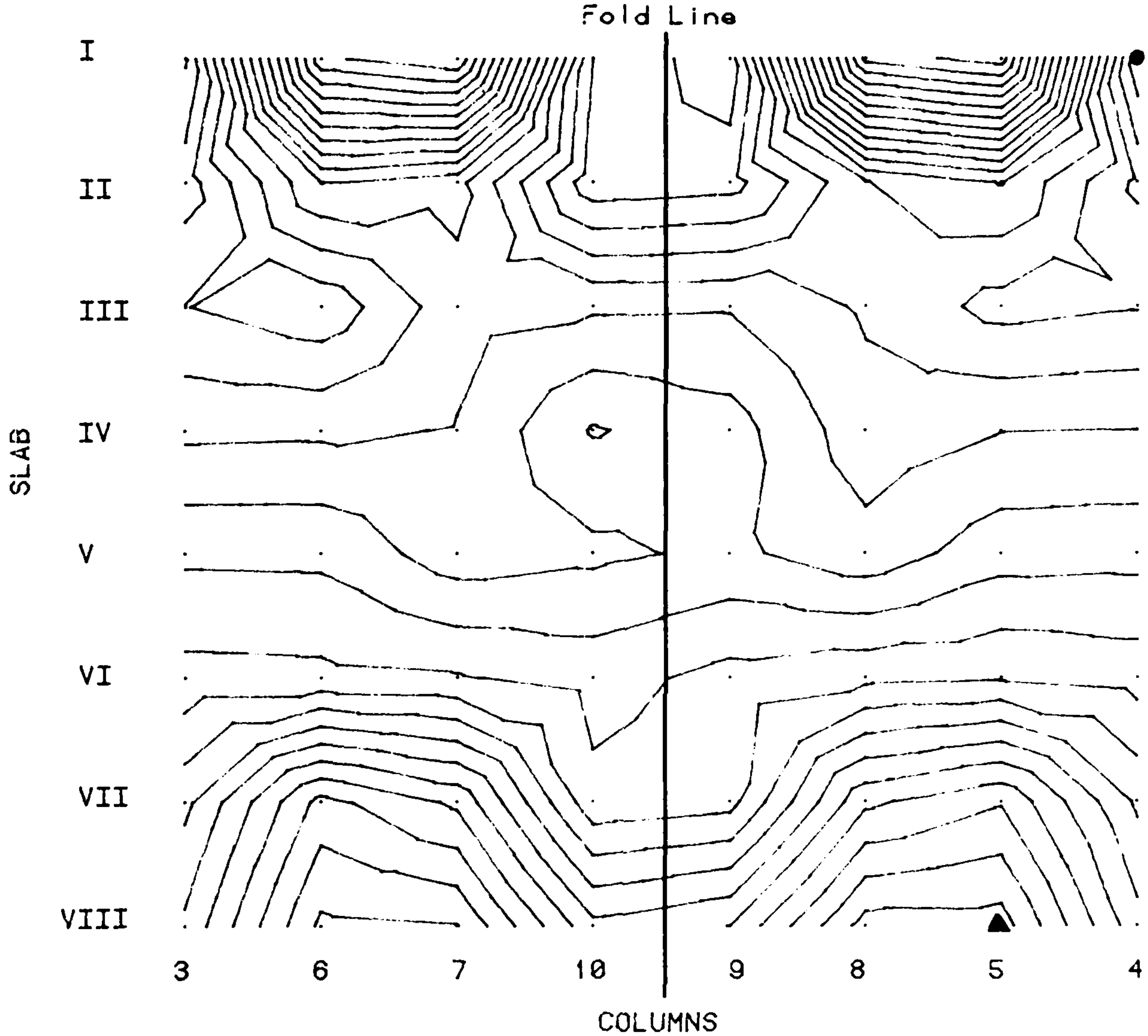


▲ Maximum Percent Relative Density, 72.33

● Minimum Percent Relative Density, 59.06

Contour line spacing is 1 percent relative density.

Fig.C19. Density contour, specimen no.43

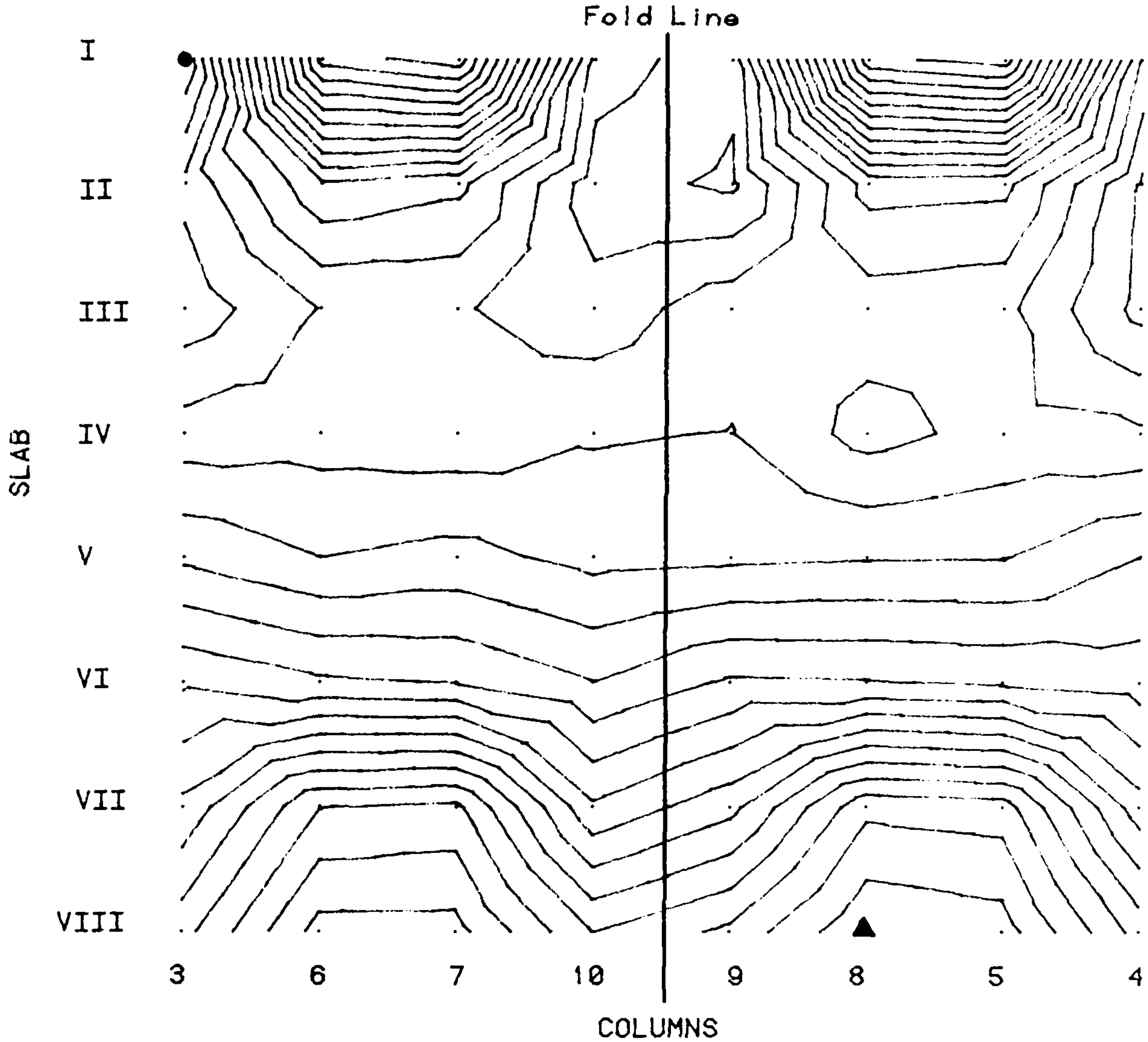


▲ Maximum Percent Relative Density, 73.46

● Minimum Percent Relative Density, 55.17

Contour line spacing is 1 percent relative density.

Fig.C20. Density contour, specimen no.44

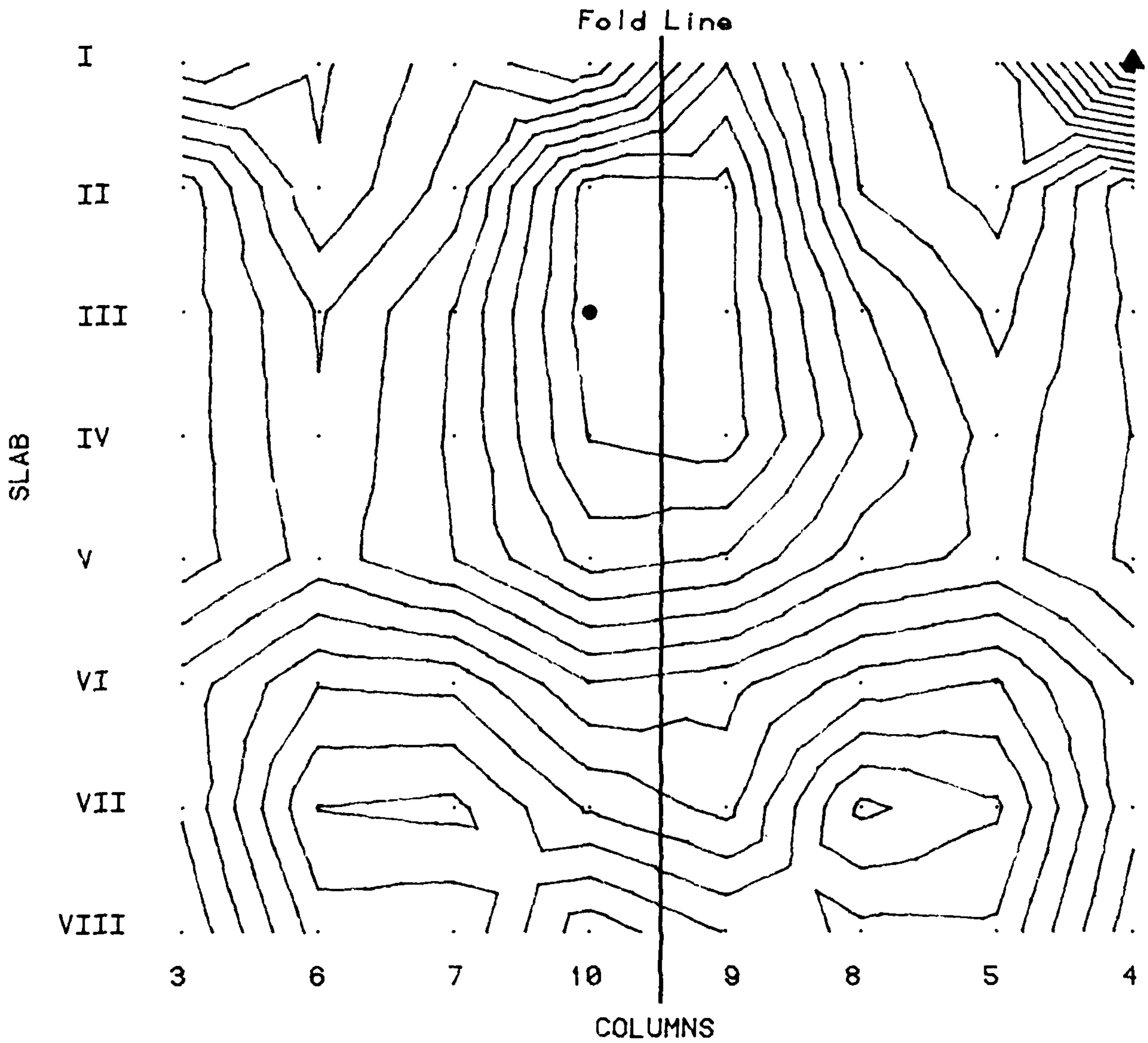


▲ Maximum Percent Relative Density, 73.87

● Minimum Percent Relative Density, 55.15

Contour line spacing is 1 percent relative density.

Fig.C21. Density contour, specimen no.45

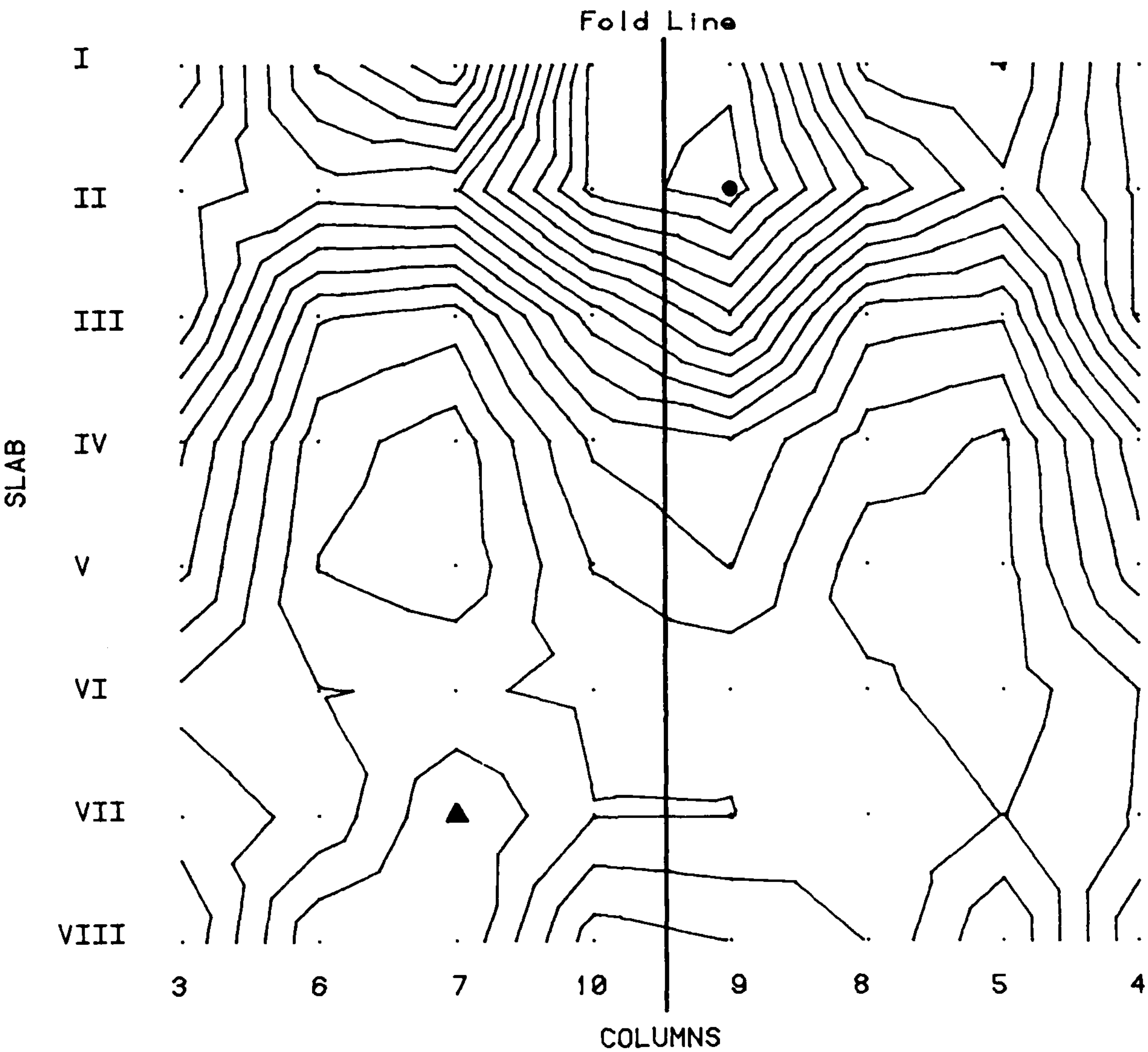


▲ Maximum Percent Relative Density, 74.90

● Minimum Percent Relative Density, 57.41

Contour line spacing is 1 percent relative density.

Fig.C22. Density contour, specimen no.46

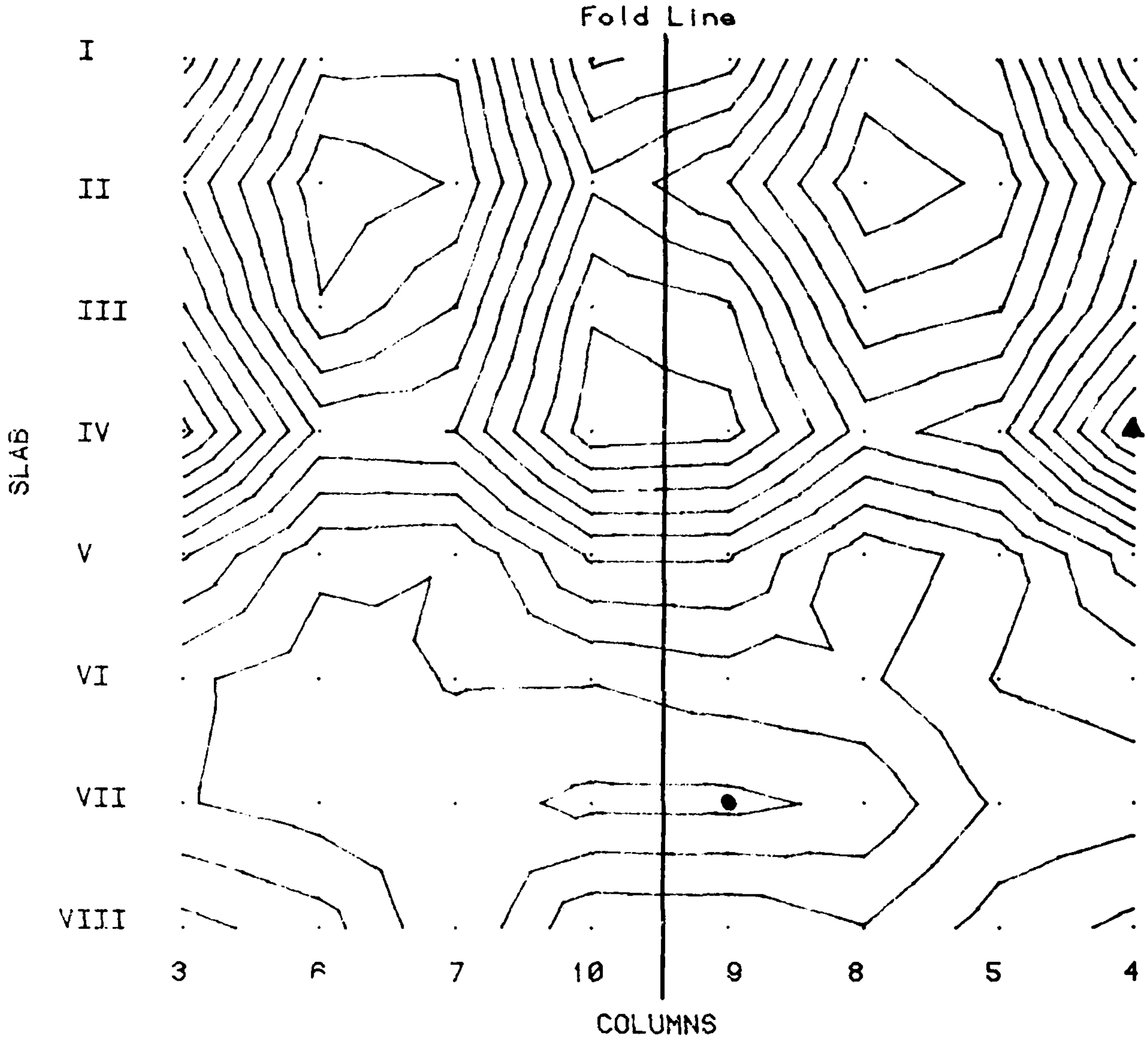


▲ Maximum Percent Relative Density, 81.00

● Minimum Percent Relative Density, 65.40

Contour line spacing is 1 percent relative density.

Fig.C23. Density contour, specimen no.47

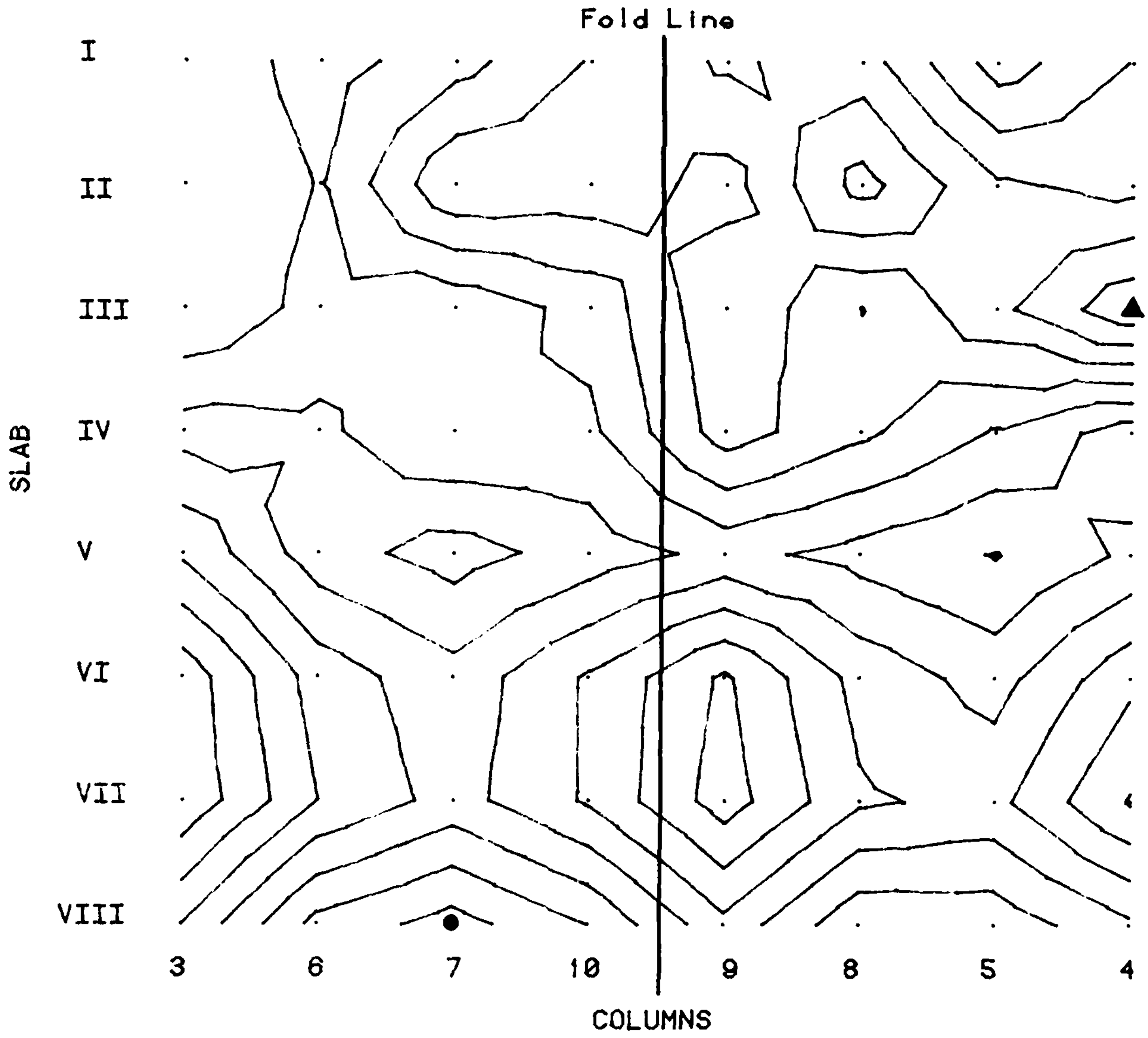


▲ Maximum Percent Relative Density, 47.32

● Minimum Percent Relative Density, 34.74

Contour line spacing is 1 percent relative density.

Fig.C24. Density contour, specimen no.49

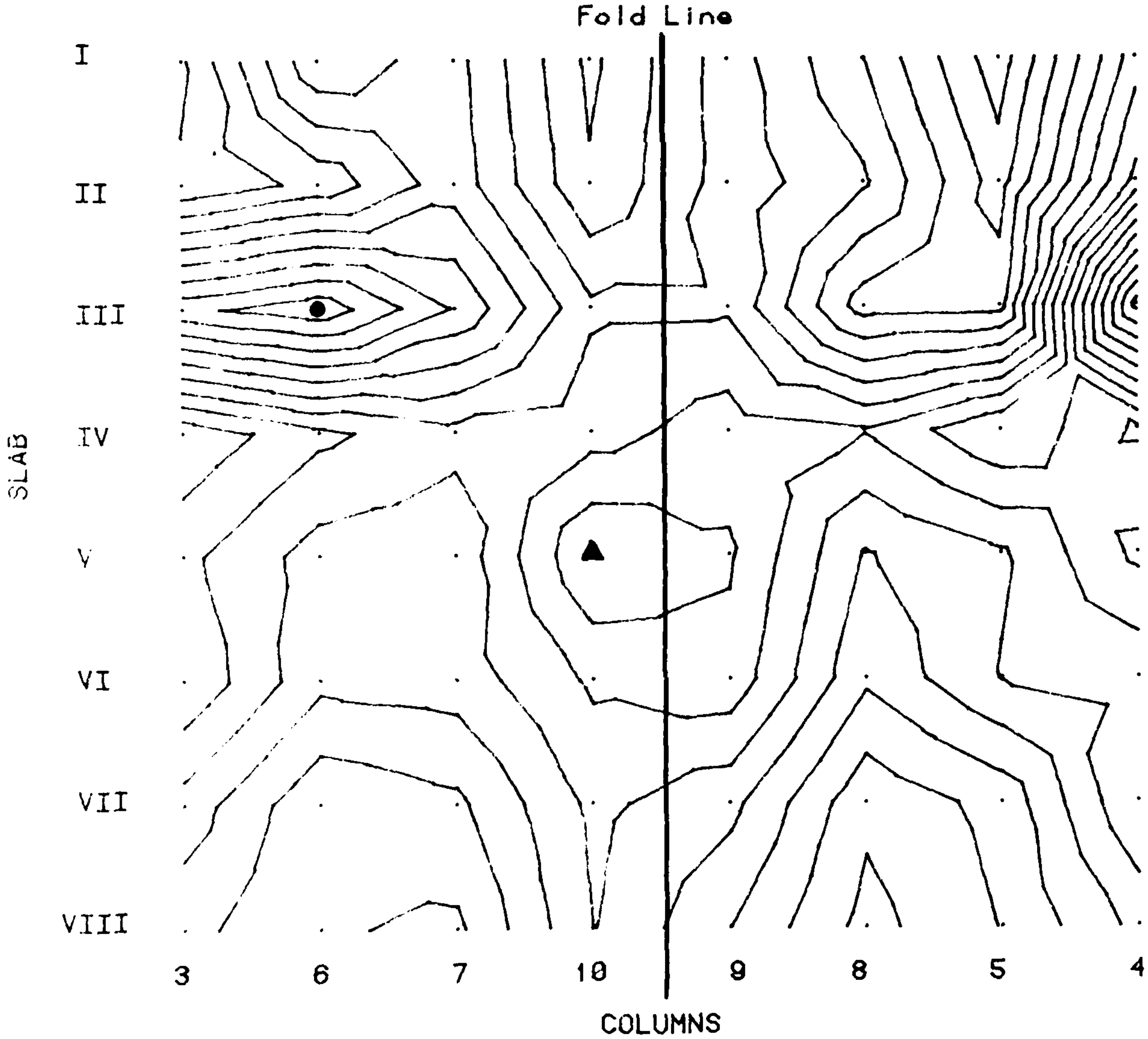


▲ Maximum Percent Relative Density, 51.76

● Minimum Percent Relative Density, 43.58

Contour line spacing is 1 percent relative density.

Fig.C25. Density contour, specimen no.50



▲ Maximum Percent Relative Density, 50.99

● Minimum Percent Relative Density, 41.30

Contour line spacing is 1 percent relative density.

Fig.C26. Density contour, specimen no.51

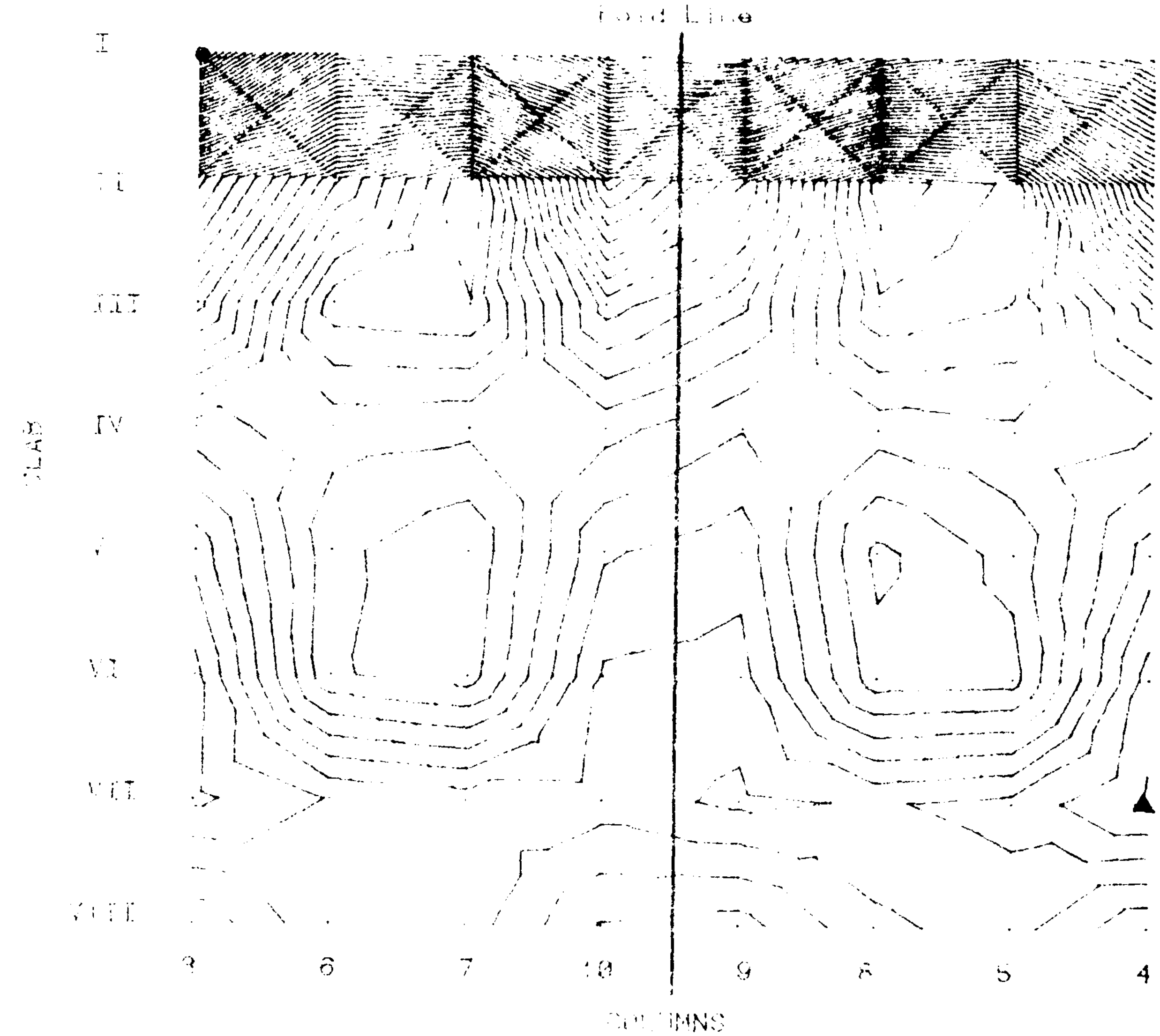
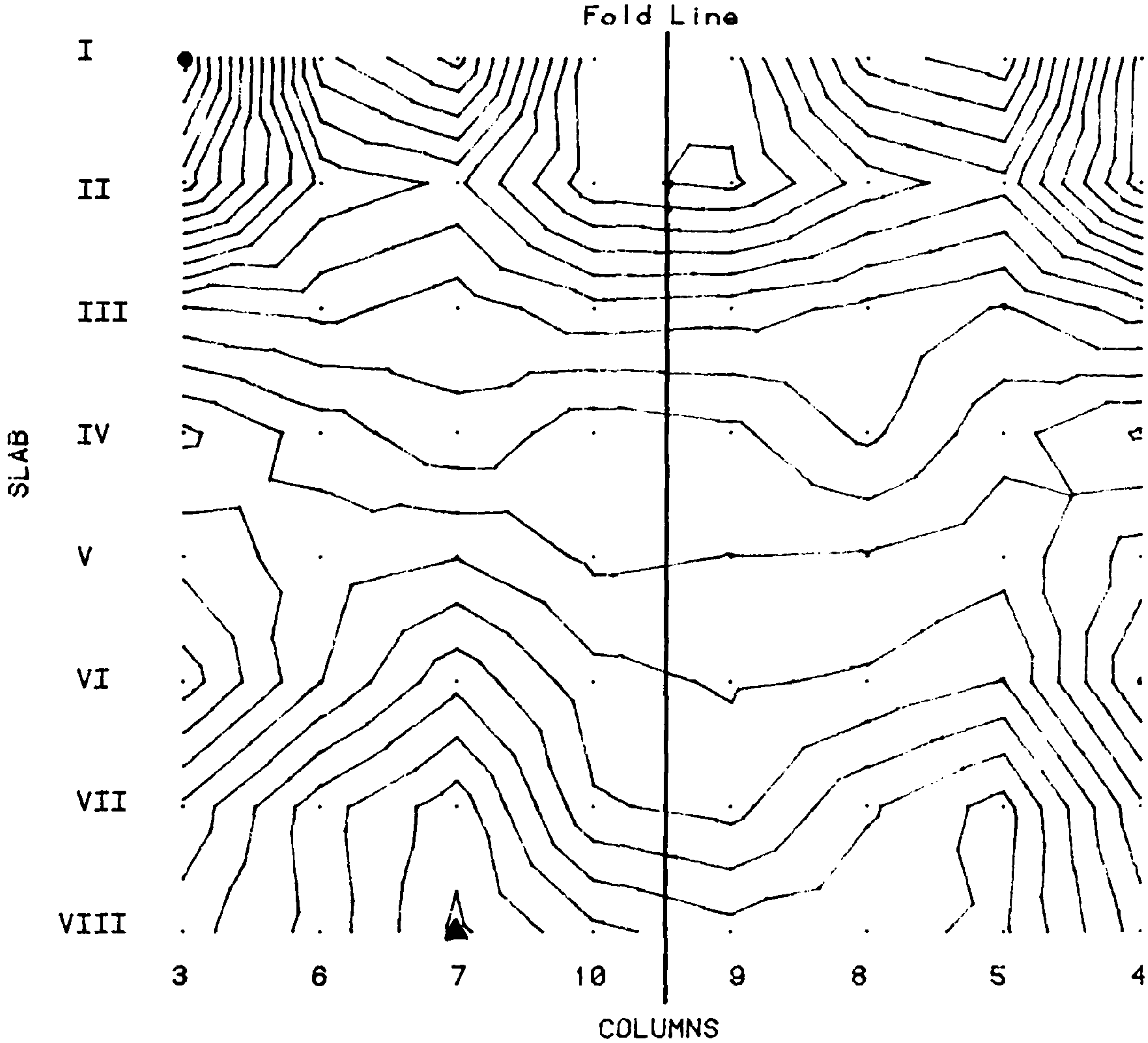


Fig. 27 Density contour - specimen no.52

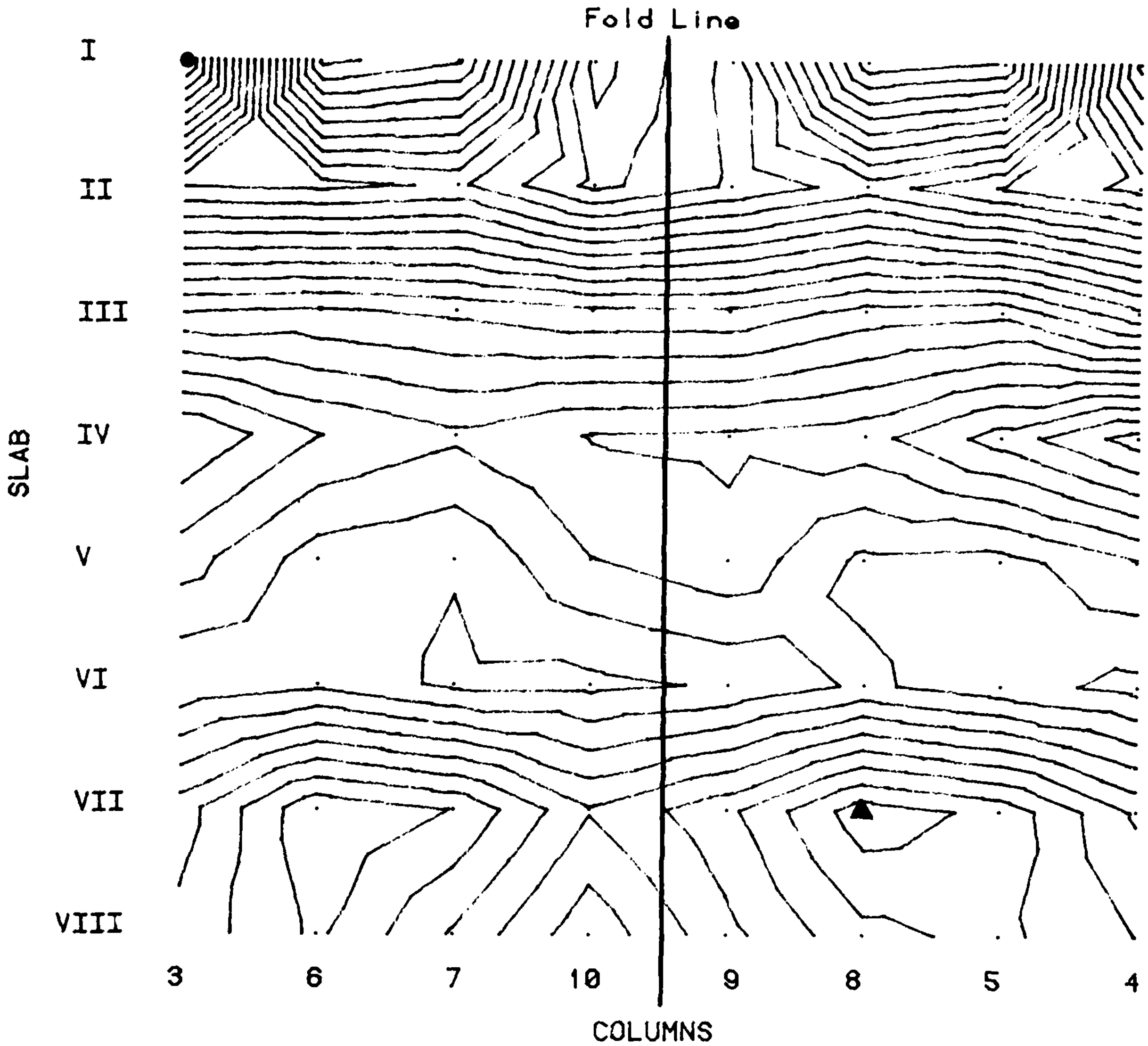


▲ Maximum Percent Relative Density, 54.20

● Minimum Percent Relative Density, 31.63

Contour line spacing is 1 percent relative density.

Fig.C28. Density contour, specimen no.53

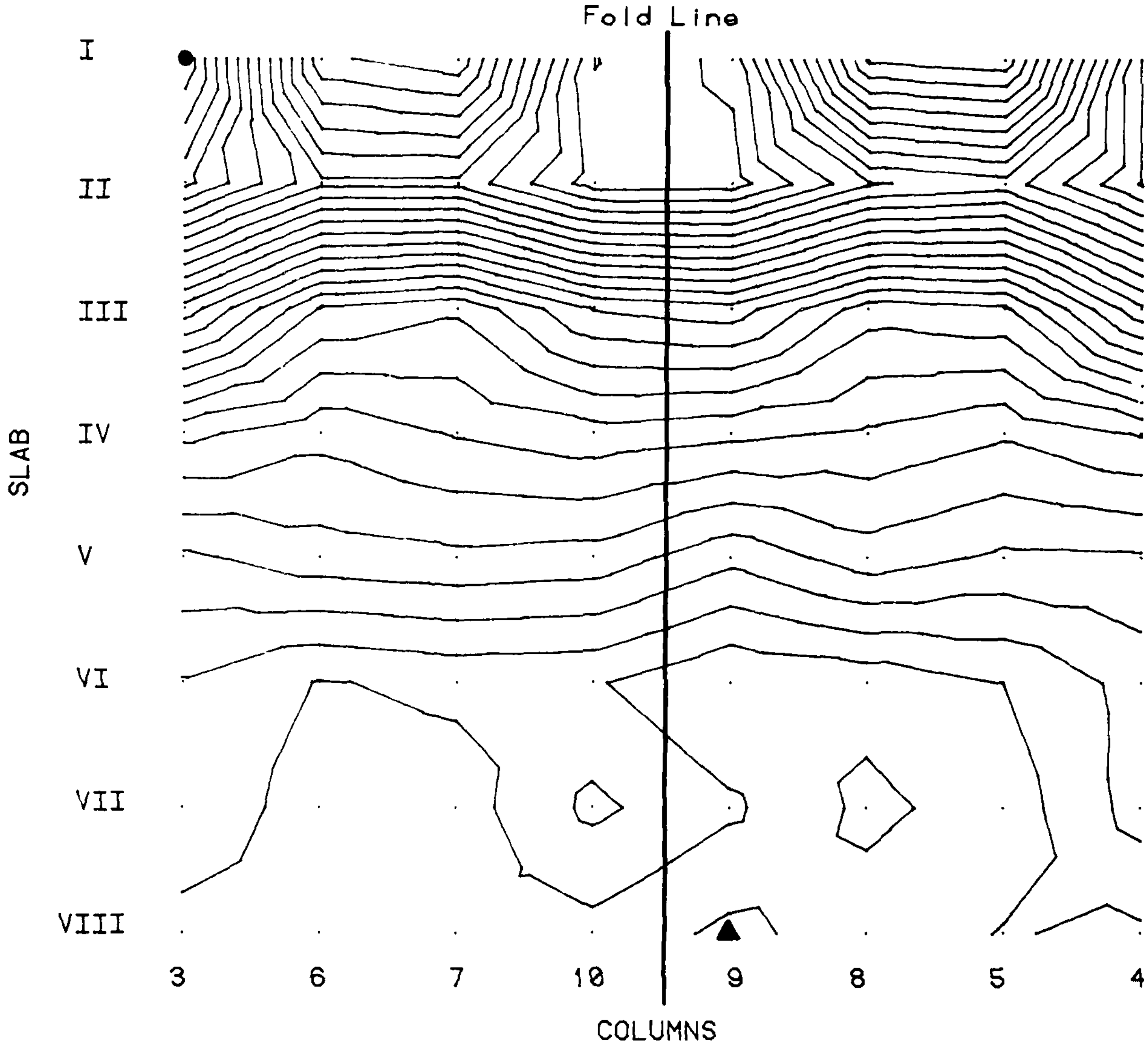


▲ Maximum Percent Relative Density, 53.58

● Minimum Percent Relative Density, 25.58

Contour line spacing is 1 percent relative density.

Fig.C29. Density contour, specimen no.54

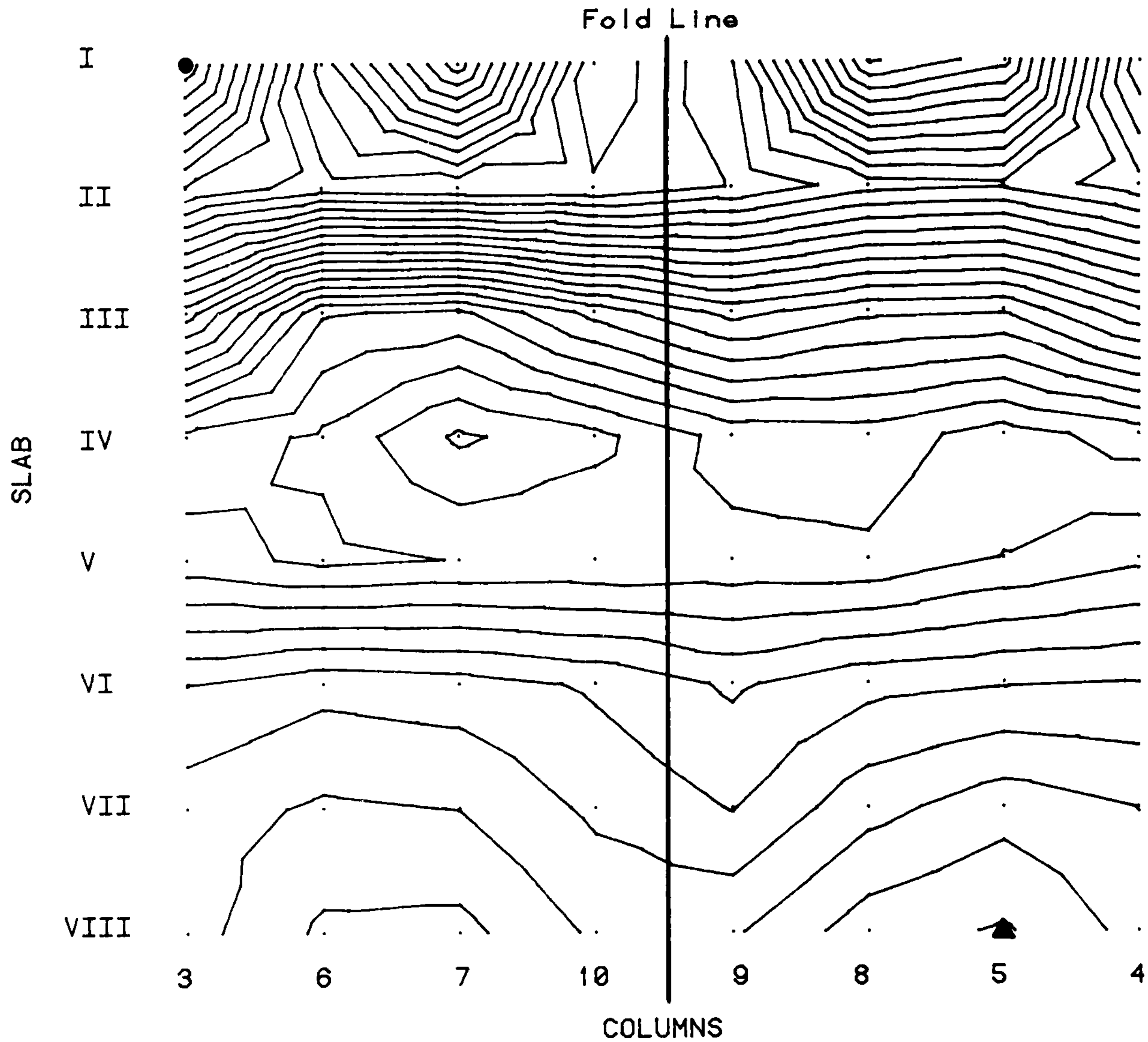


▲ Maximum Percent Relative Density, 52.23

● Minimum Percent Relative Density, 24.11

Contour line spacing is 1 percent relative density.

Fig.C30. Density contour, specimen no.55



▲ Maximum Percent Relative Density, 56.11

● Minimum Percent Relative Density, 22.18

Contour line spacing is 1 percent relative density.

Fig.C31. Density contour, specimen no.56

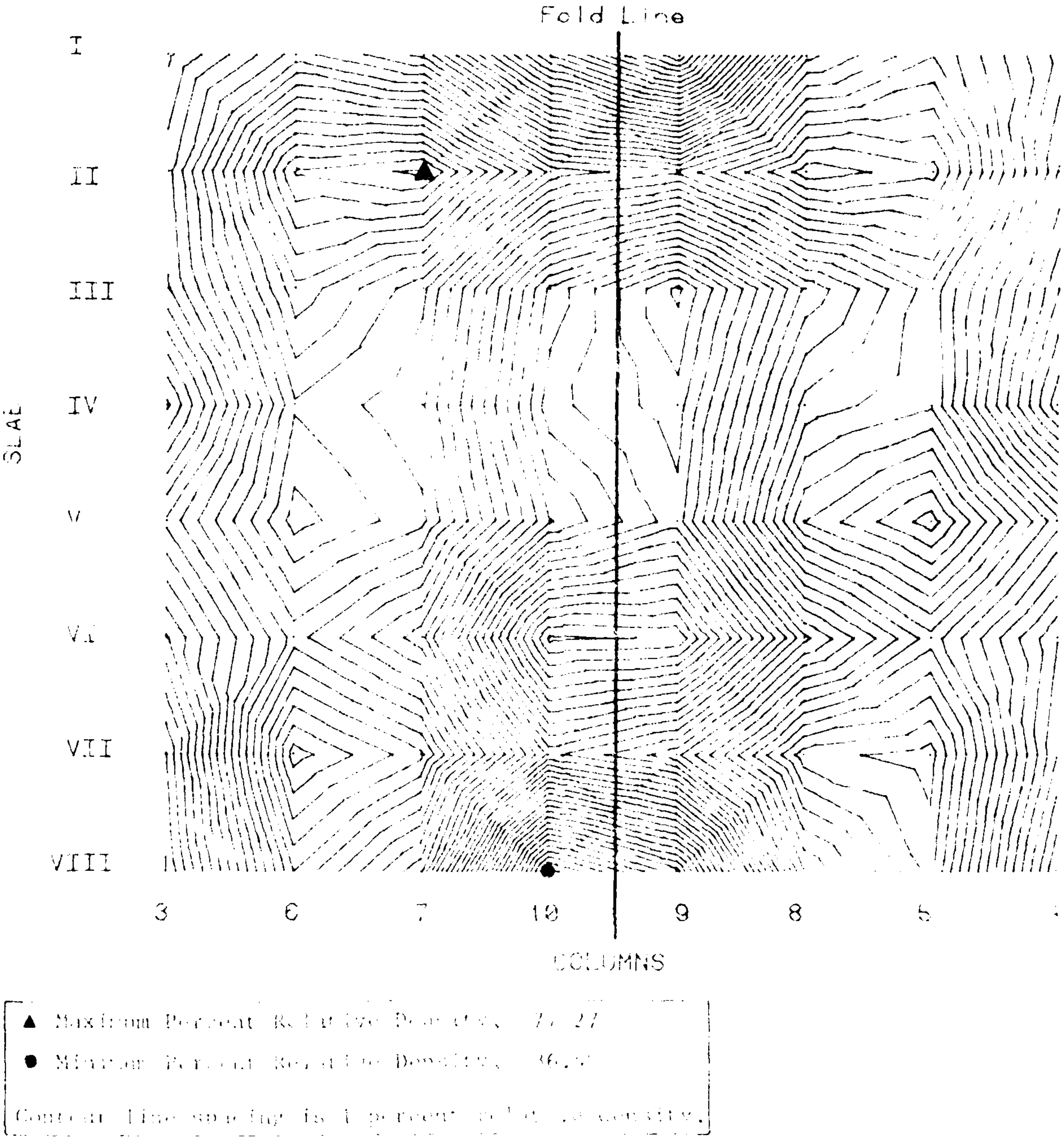


Fig 032. Density contour, specimen no 57

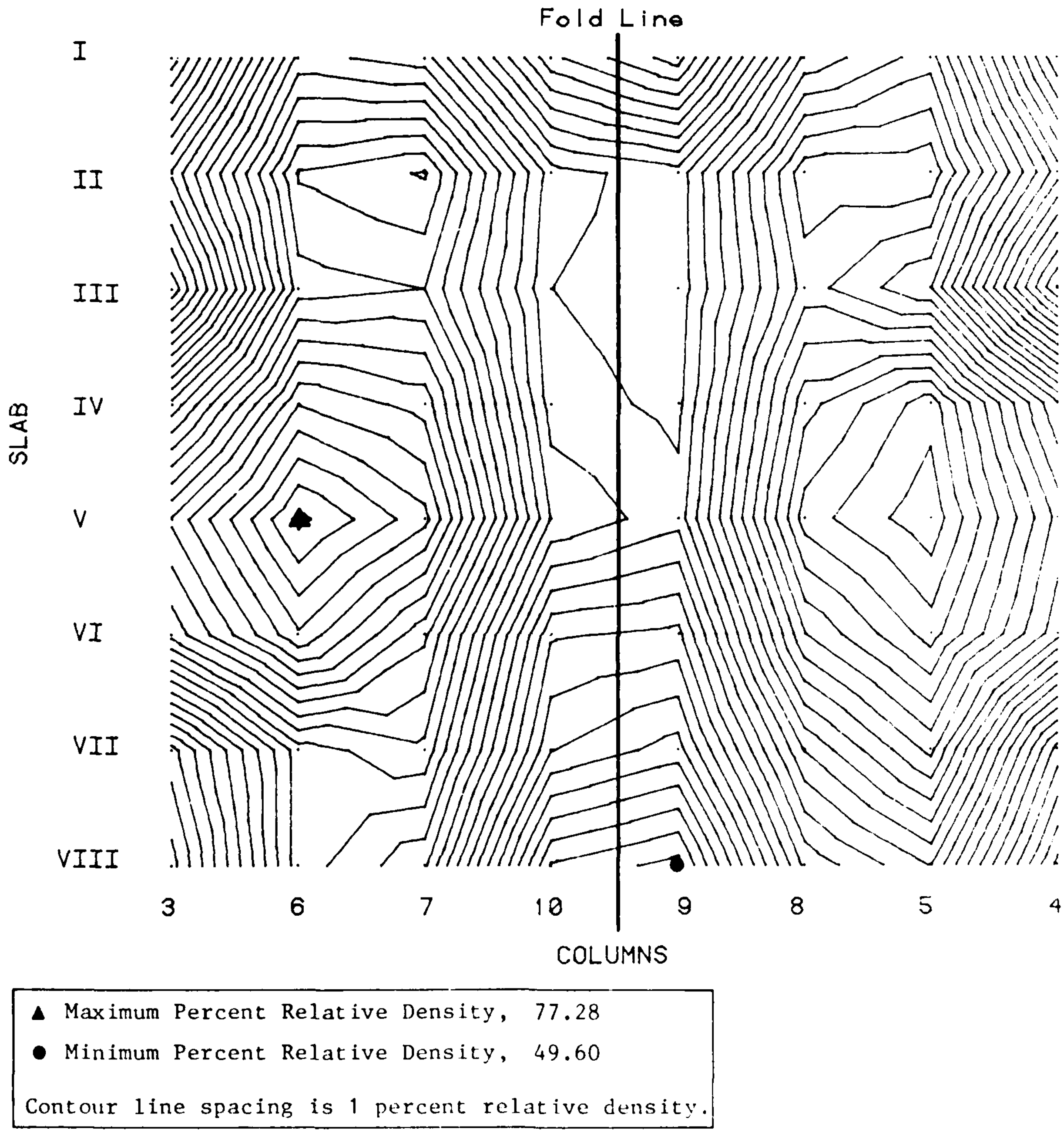
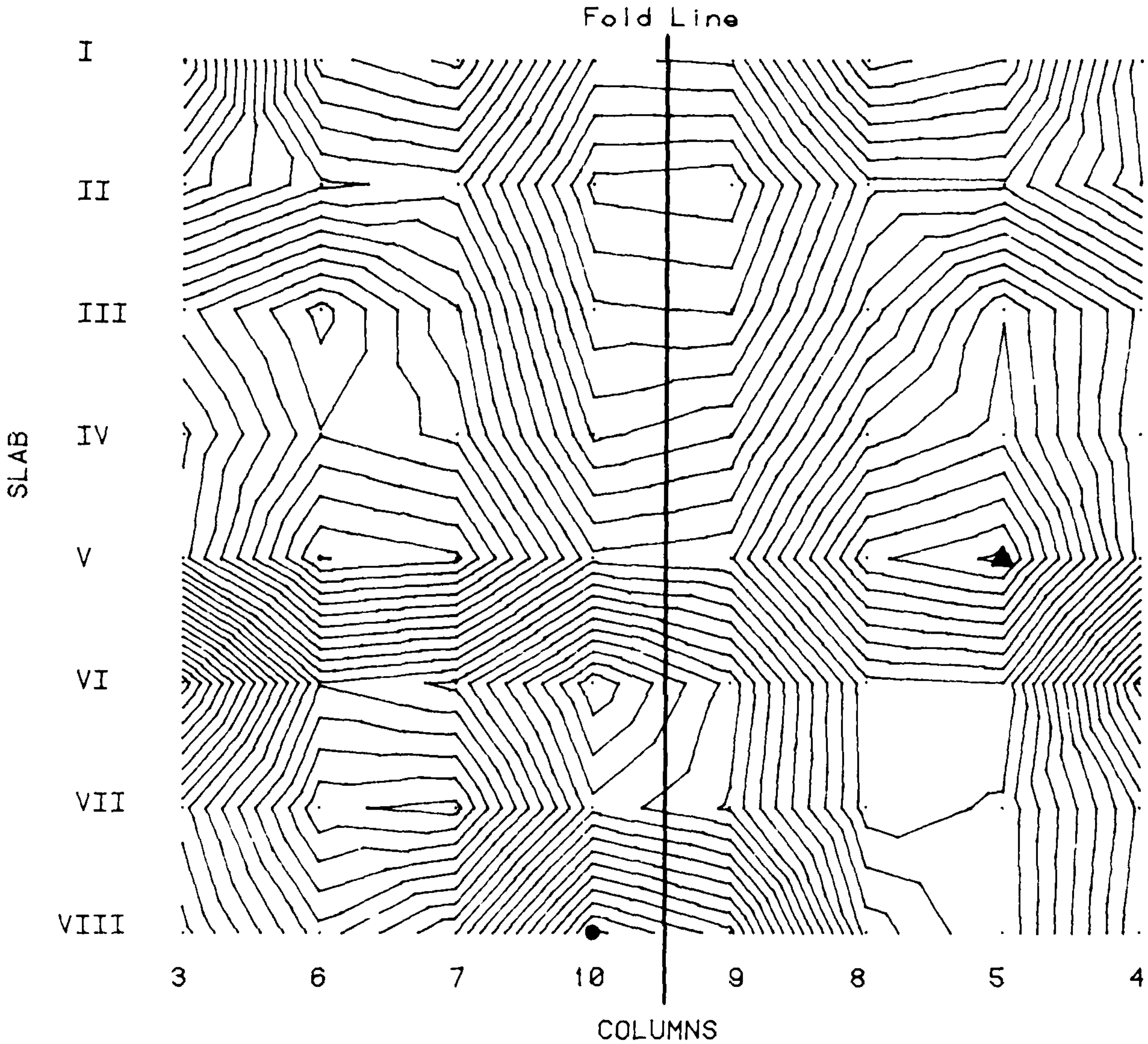


Fig.C33. Density contour, specimen no.58

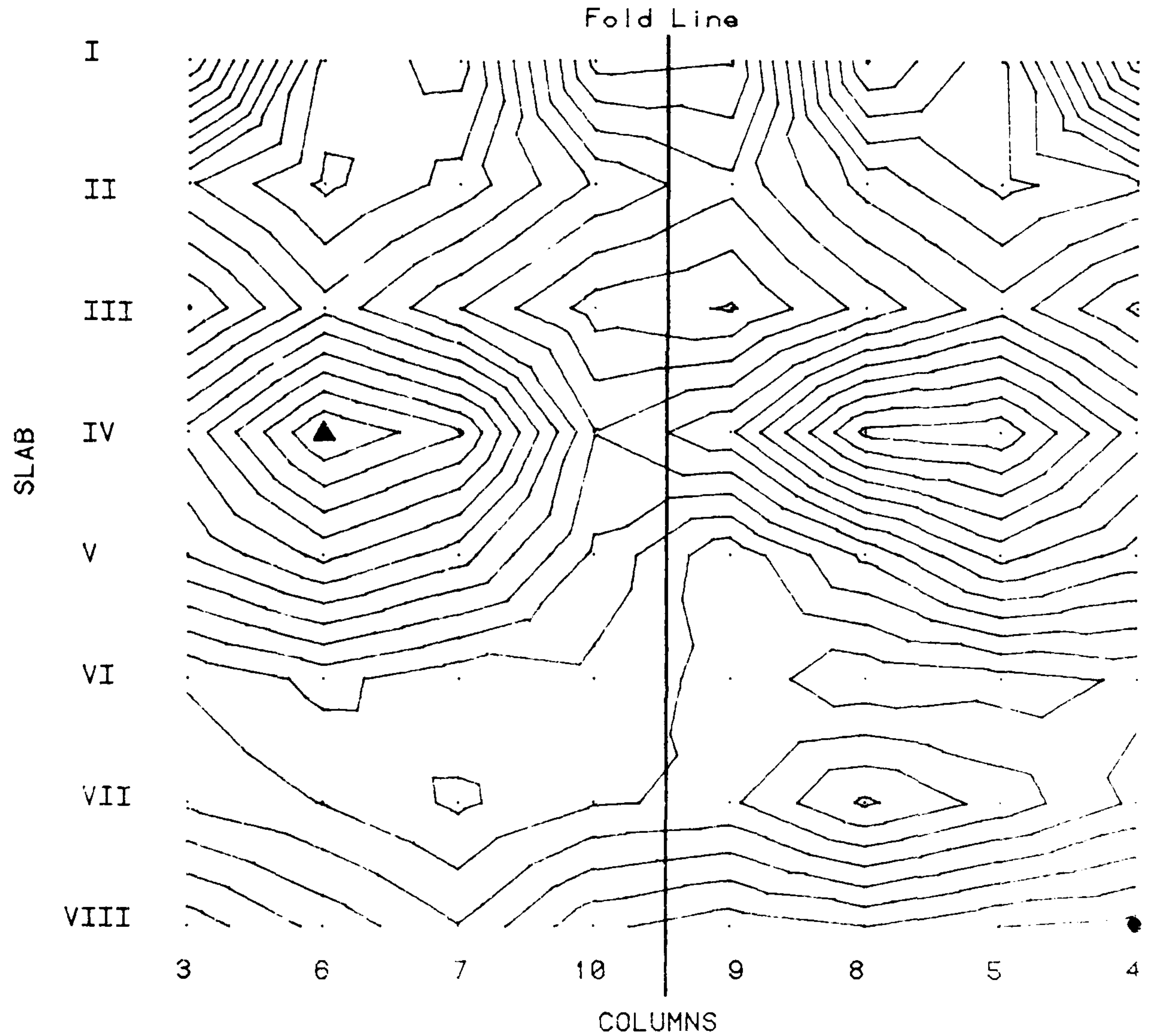


▲ Maximum Percent Relative Density, 74.28

● Minimum Percent Relative Density, 45.69

Contour line spacing is 1 percent relative density.

Fig.C34. Density contour, specimen no.59



▲ Maximum Percent Relative Density, 71.08

● Minimum Percent Relative Density, 53.63

Contour line spacing is 1 percent relative density.

Fig.C35. Density contour, specimen no.C0

AD-A148 944 INVESTIGATION OF DENSITY VARIATION IN TRIAXIAL TEST SPECIMENS OF COHESION..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS GEOTE.. P A GILBERT 3/3

UNCLASSIFIED SEP 84 WES/TR/GL-84-10 F/G 8/13 NL

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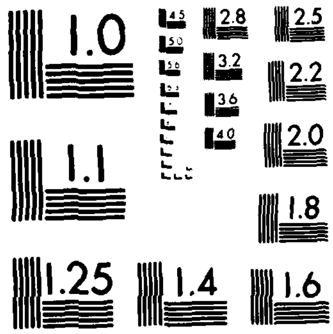
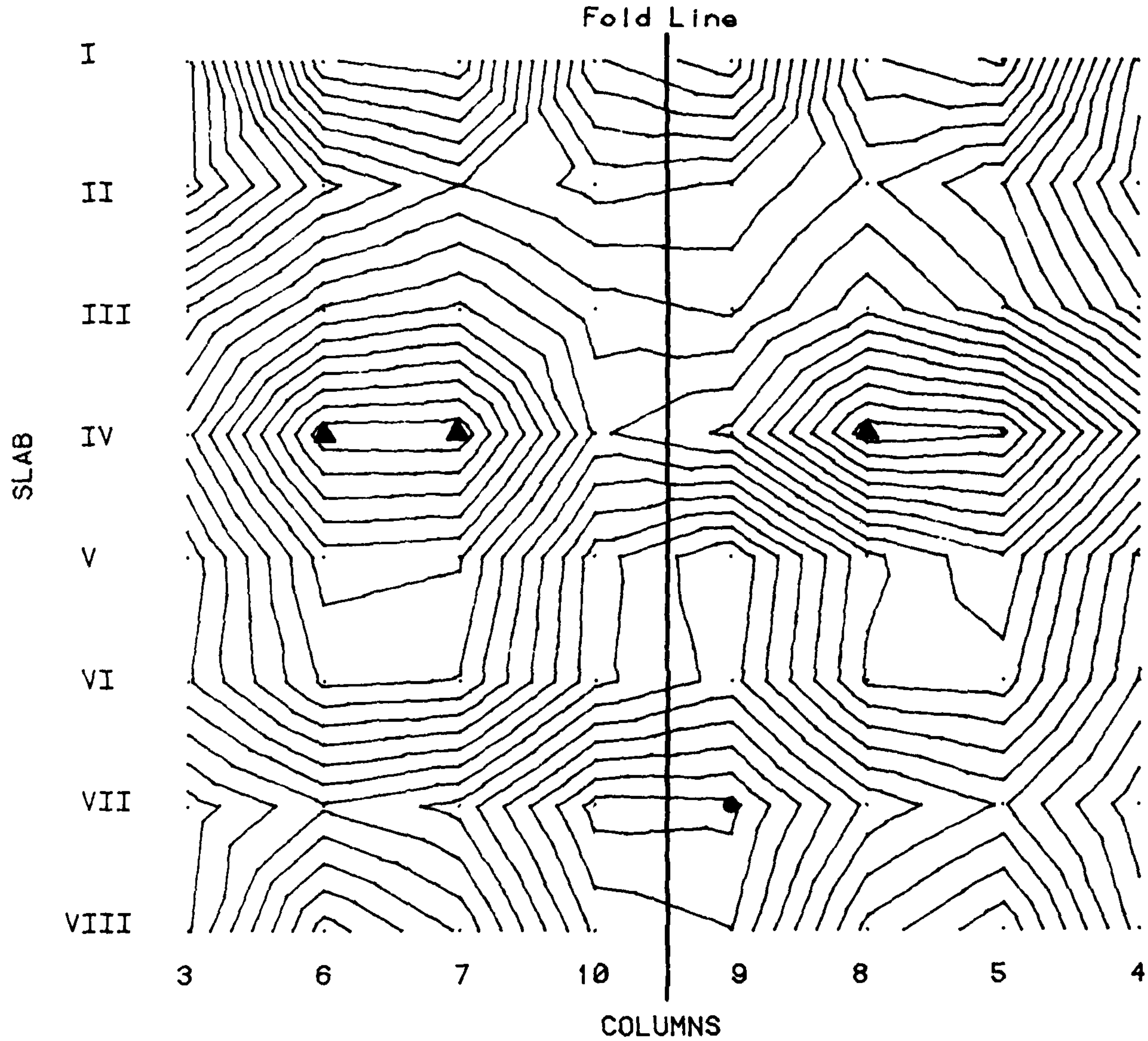


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

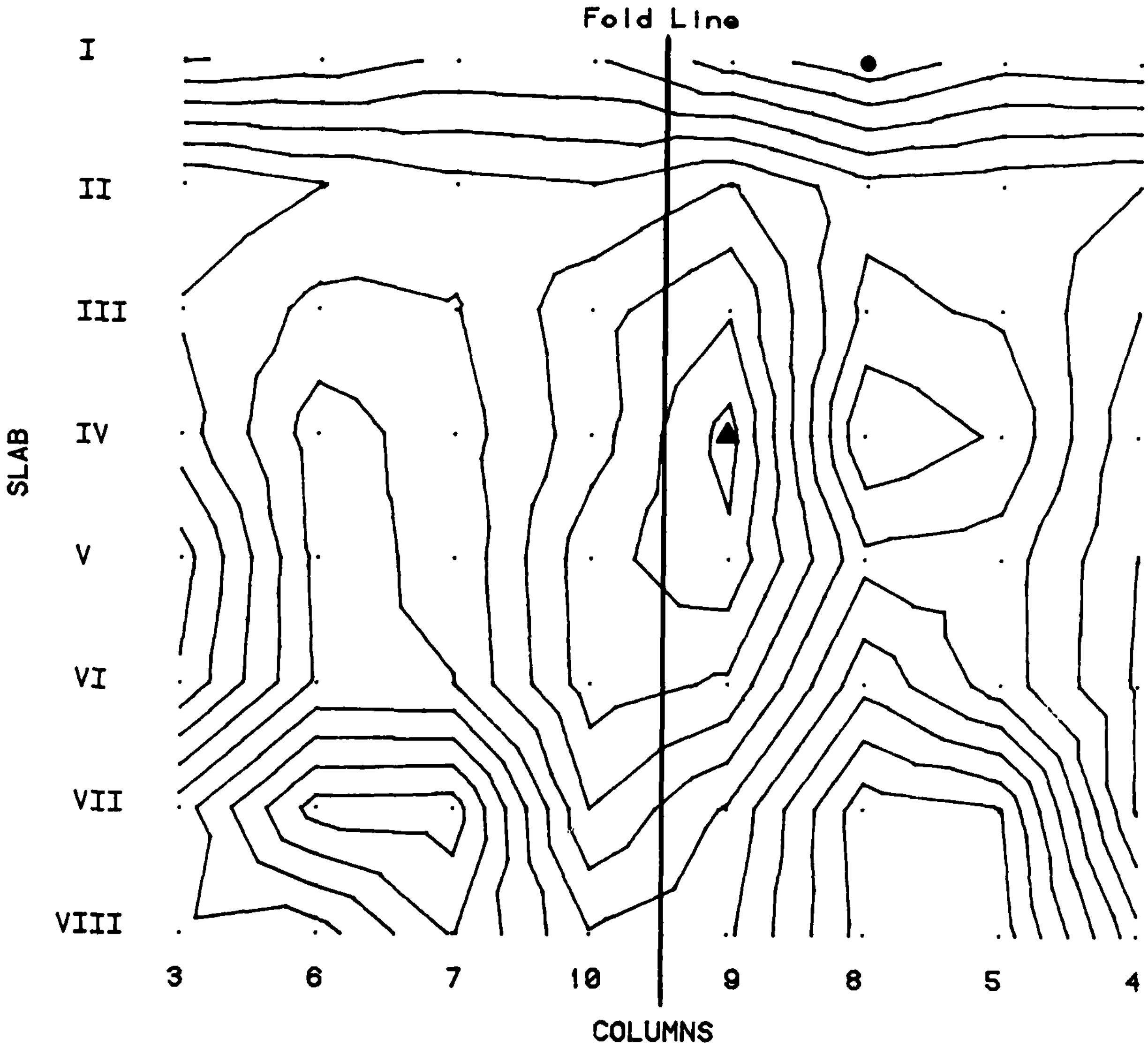


▲ Maximum Percent Relative Density, 72.64

● Minimum Percent Relative Density, 53.71

Contour line spacing is 1 percent relative density.

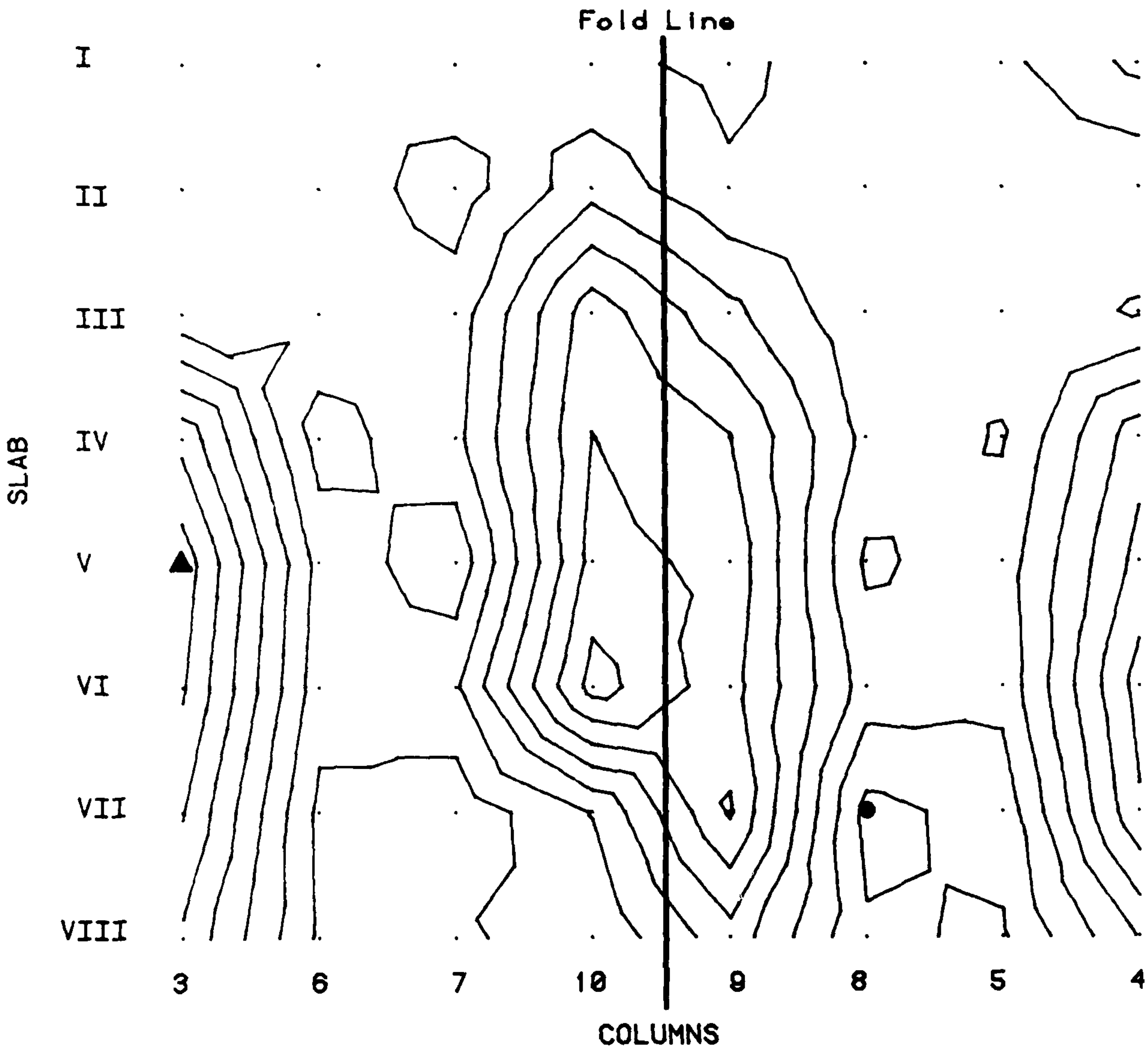
Fig.C36. Density contour, specimen no.61



▲ Maximum Percent Relative Density,	45.37
● Minimum Percent Relative Density,	35.29

Contour line spacing is 1 percent relative density.

Fig.C37. Density contour, specimen no.62

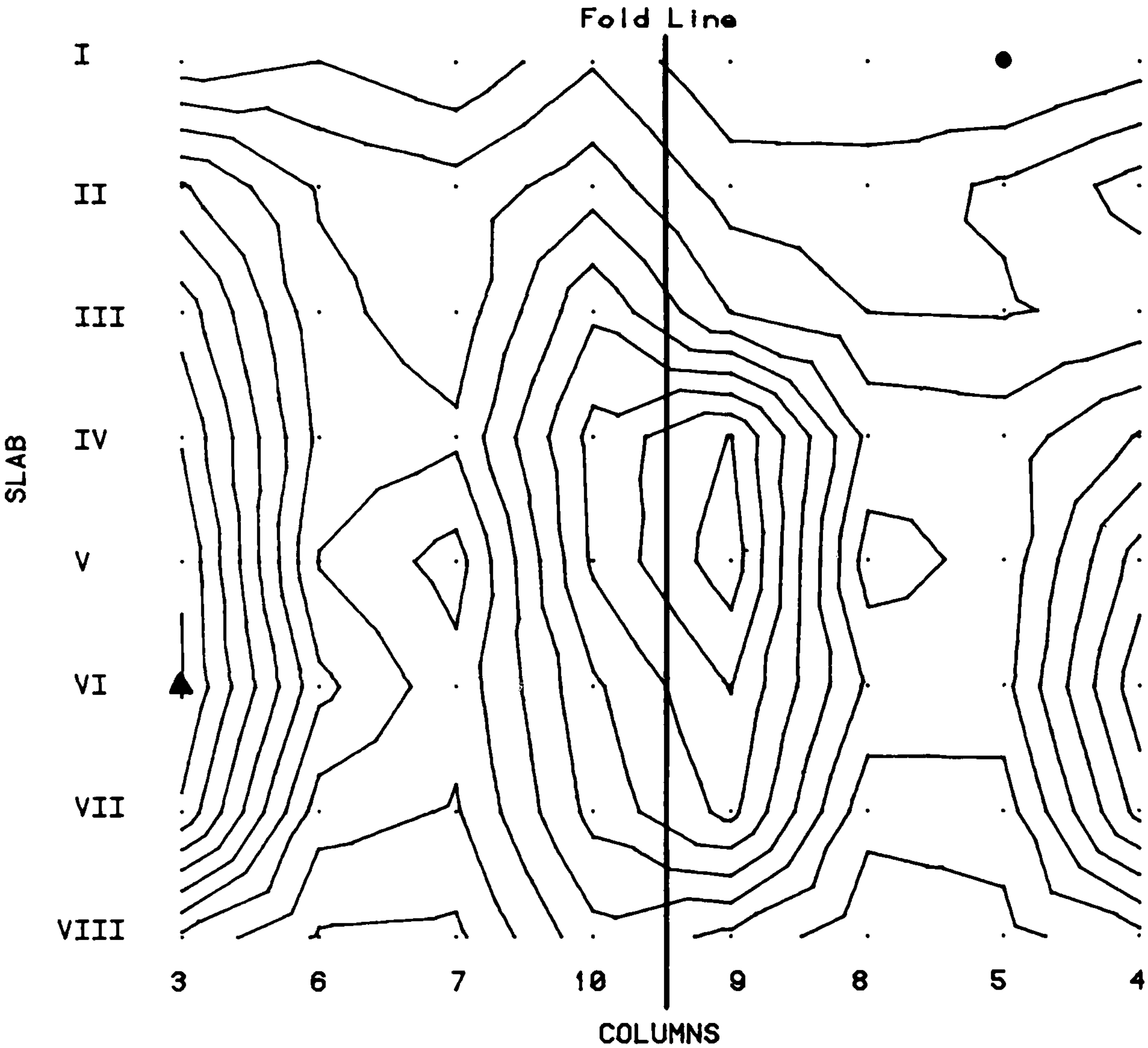


▲ Maximum Percent Relative Density, 42.60

● Minimum Percent Relative Density, 34.70

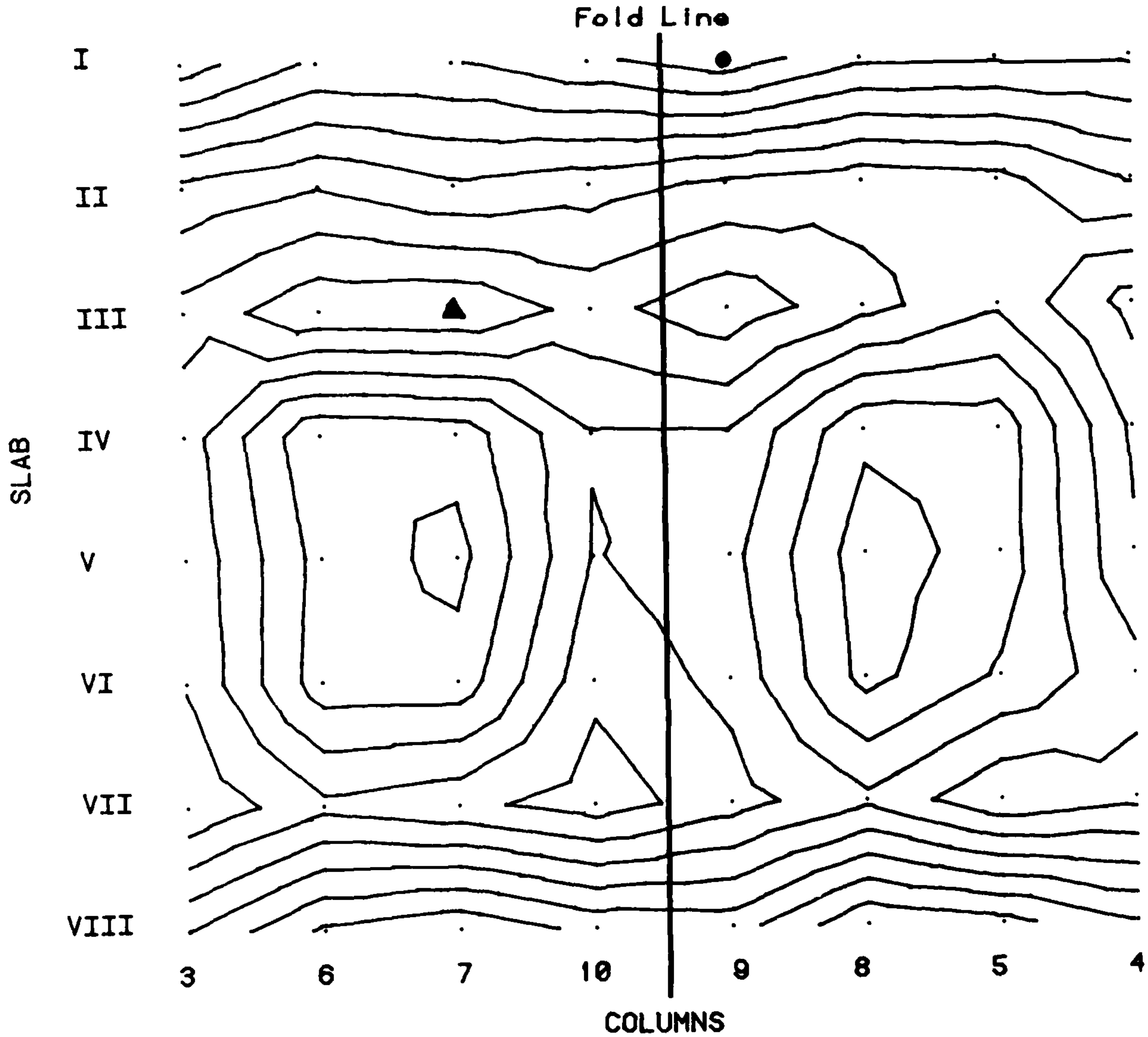
Contour line spacing is 1 percent relative density.

Fig.C38. Density contour, specimen no.63



▲ Maximum Percent Relative Density, 44.10
● Minimum Percent Relative Density, 33.65
Contour line spacing is 1 percent relative density.

Fig.C39. Density contour, specimen no.64

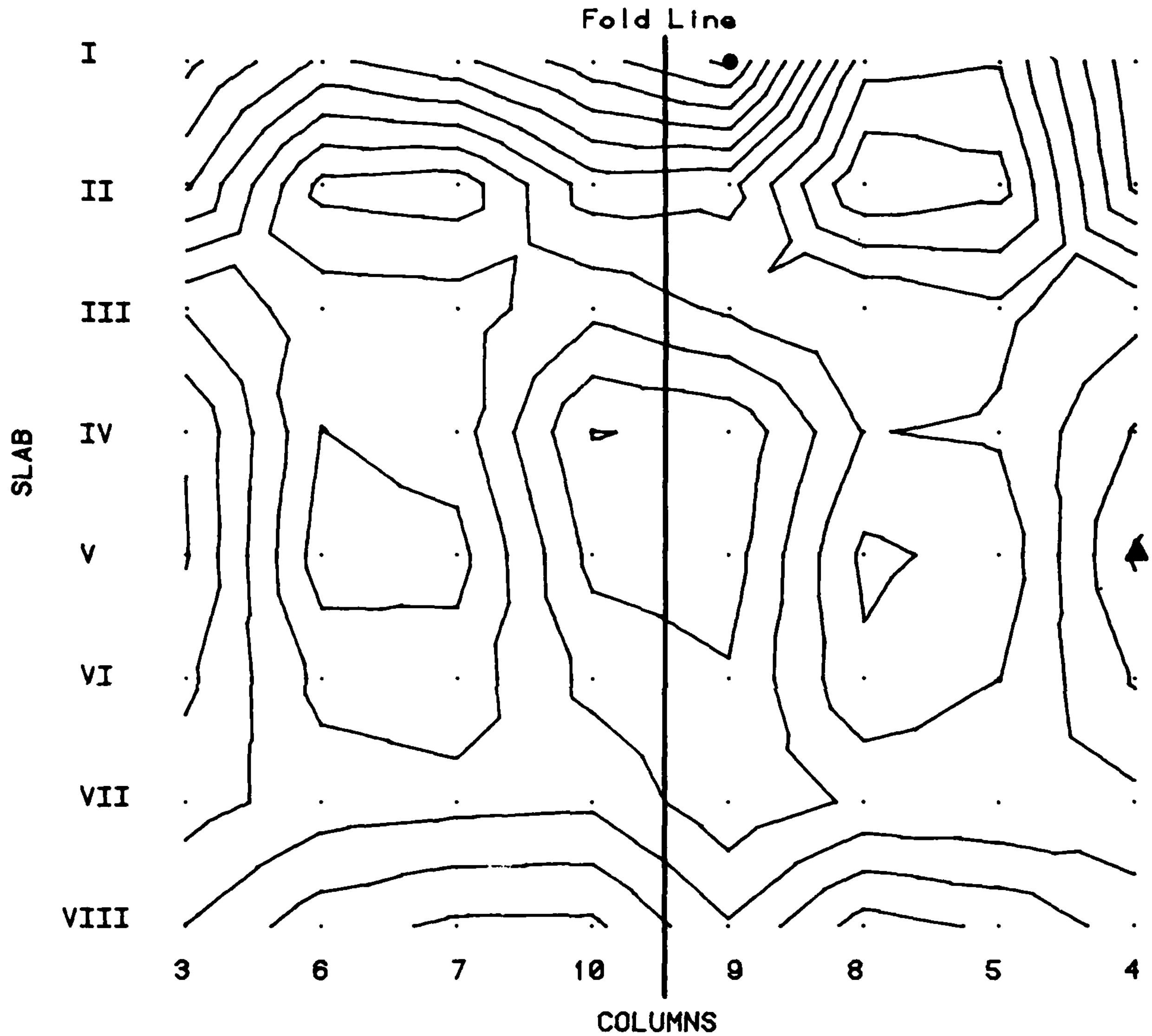


▲ Maximum Percent Relative Density, 40.87

● Minimum Percent Relative Density, 32.38

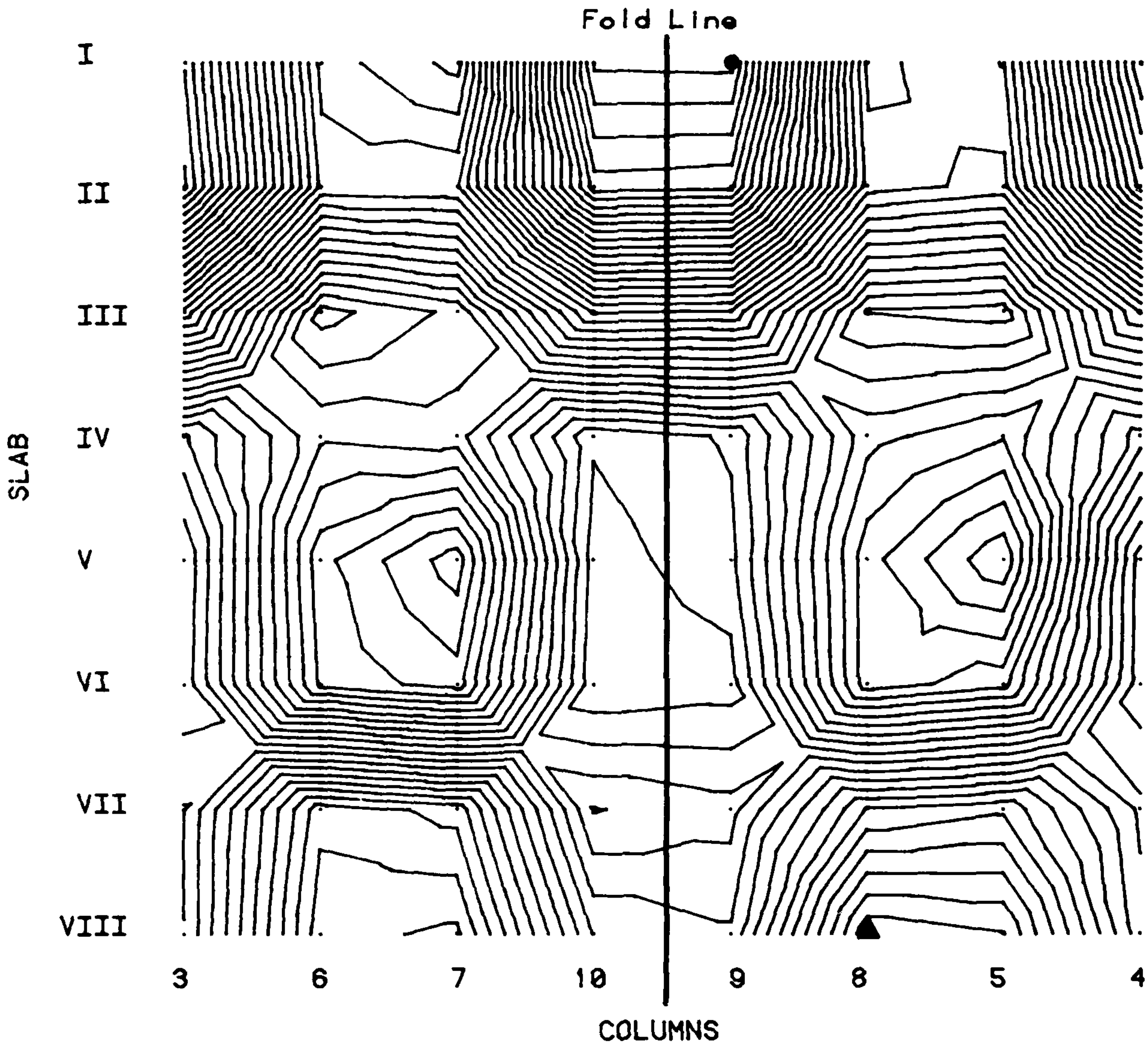
Contour line spacing is 1 percent relative density.

Fig.C40. Density contour, specimen no.66



▲ Maximum Percent Relative Density,	40.12
● Minimum Percent Relative Density,	29.79
Contour line spacing is 1 percent relative density.	

Fig.C41. Density contour, specimen no.67

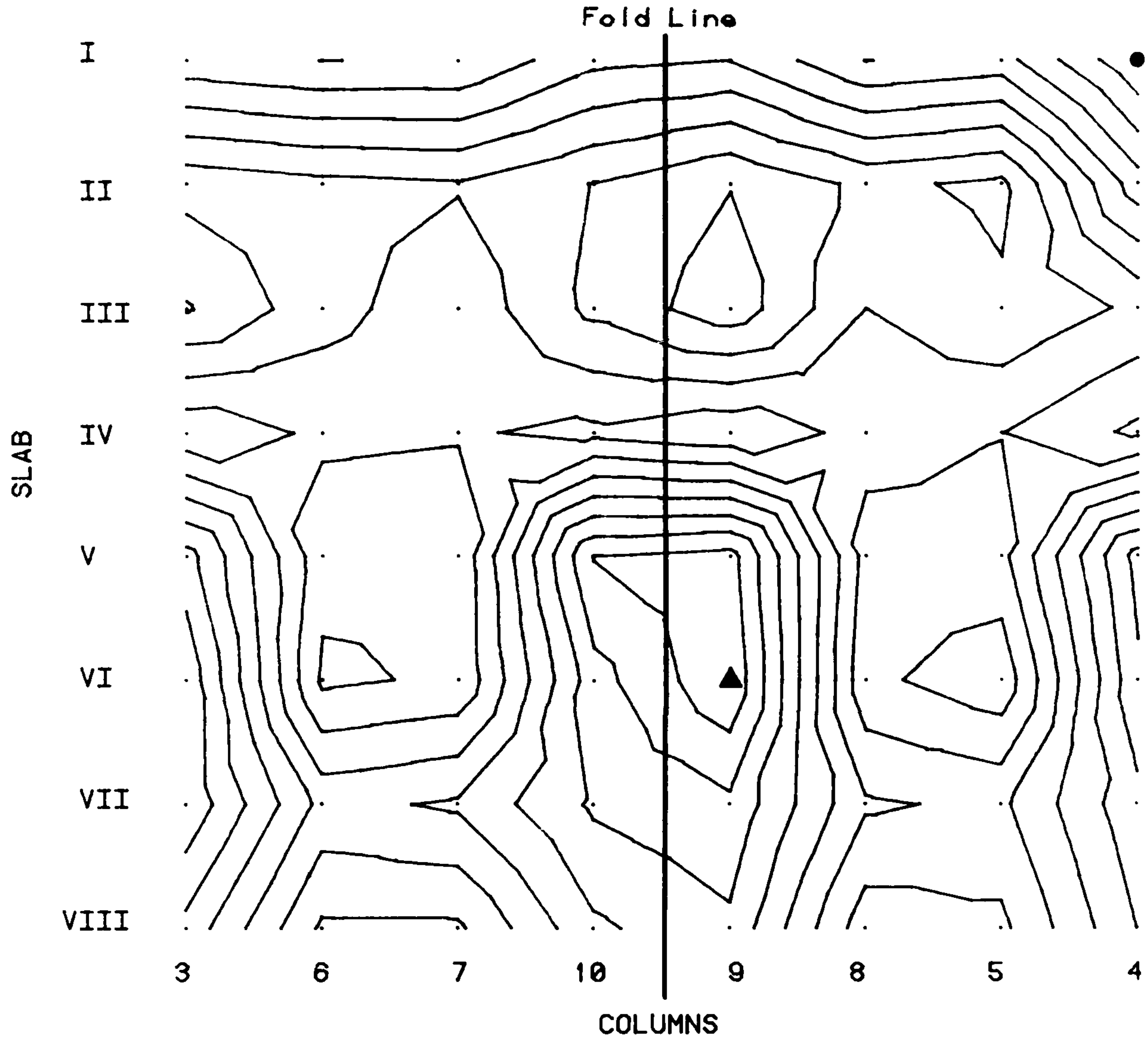


▲ Maximum Percent Relative Density, 48.76

● Minimum Percent Relative Density, 5.68

Contour line spacing is 1 percent relative density.

Fig.C42. Density contour, specimen no.68



▲ Maximum Percent Relative Density, 55.85

● Minimum Percent Relative Density, 43.05

Contour line spacing is 1 percent relative density.

Fig.C43. Density contour, specimen no.69/70

APPENDIX D

EARLY INVESTIGATIONS OF DENSITY UNIFORMITY

Pluviation Through Air

Specimen placement

1. Reid-Bedford model sand was initially used in this investigation. It is a uniform fine sand taken from Campbell Swamp on the Big Black River in west central Mississippi. The sand consists predominantly of tan to light brown quartz particles. It is a subrounded to subangular material and contains less than 5 percent muscovite and no more than 1 to 2 percent heavy minerals. The sand contains no magnetic material and is free of organic matter.

2. The D_{50} size is about 0.24 mm and the coefficient of uniformity is 1.6. The average specific gravity is 2.65 and the maximum and minimum dry unit weights as determined according to EM 1110-2-1906 are 103.4 pcf and 88.1 pcf, respectively. The amount of material passing the No. 200 sieve varied anywhere from a fraction of a percent to over 3 percent. The material initially used early in this investigation was determined to contain 1.2 percent minus 200 material and was obtained from large stockpiles stored at WES.

3. The first attempt at molding uniform specimens employed the technique of dry pluviation through air. Sand was placed in a circular cylindrical hopper with a perforated plate at the bottom. A hand-held plate was placed over the bottom of the hopper to hold back the flow of sand until the desired moment of release. The height of all of the sand grains was 10 in. This distance was determined from the depth of the mold, 9 in., plus a 1-in. clearance for the plate, including some clearance to adjust the plate and ultimately remove it. When the sand was released, the hopper was lifted with a rack-and-pinion device mounted on the triaxial baseplate in such a manner that a constant 10-in. height of drop was maintained between the bottom of the hopper and the top of the forming specimen. The diameter of the hopper was 6 in. and the diameter of the specimen 4 in. The sand rained into the cylindrical mold which sat on the triaxial base. The rack-and-pinion device with the hopper is shown in Figure D1; it was bolted onto the triaxial base over the mold. The handle of the device was turned to raise the hopper at the same rate that the specimen surface rose during deposition. Operating in this manner ensured that the height of drop would be constant during specimen placement. A rubber membrane inside the mold was held securely in place with a vacuum. Forty-five seconds were required to fill the mold with material feeding freely from the

hopper. The top of the specimen was overbuilt and the excess material removed with a straightedge. The top cap was then applied and the membrane folded up onto the cap and secured with an O-ring. Vacuum was applied to the specimen and the mold removed. The specimen was then measured to obtain its initial volume. The triaxial chamber was assembled around the specimen which was then saturated and consolidated to 15-psi effective confining pressure. It should be noted that seepage saturation consisted of introducing water into the bottom of the specimen which flushed excess air out through the top. Back pressure up to about 40 psi was applied to obtain a minimum acceptable B parameter value of 0.96. Six specimens were built in this manner and five were frozen and analyzed for density uniformity. One was lost due to a membrane leak. While the initial weight of these six specimens could not be determined because of the attachment of the mold to the triaxial chamber base, another group of five specimens was prepared by the same placement method, and their initial average density (weight/volume) was determined to vary ±0.13 pcf. (The specimen weight of about 3,000 g could be reproduced to ±4 g in a mold volume of about 1,850 cm^3.) This is ±0.8 percent relative density and indicates that this procedure was extremely repeatable in terms of average density from specimen to specimen.

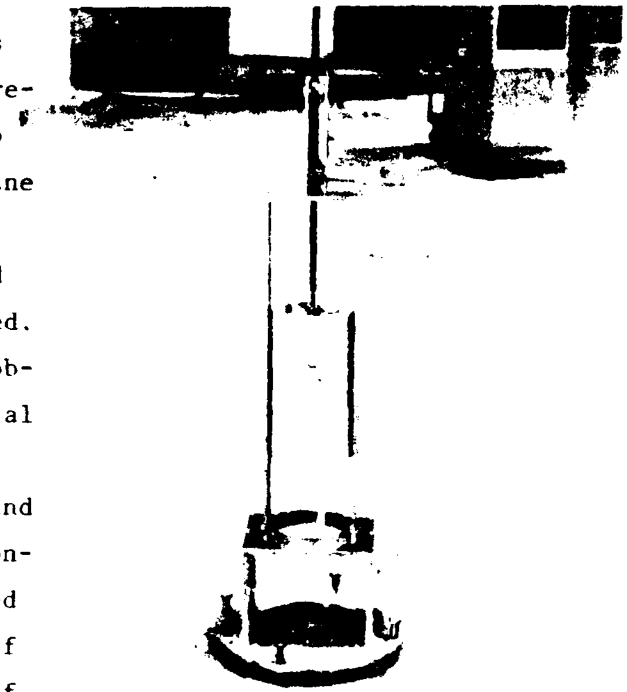


Figure D1. Rack-and-pinion device with hopper

Specimen uniformity

4. The vertical density pattern in all early specimens is shown plotted in Figure D2. Procedures for cutting the specimen were identical to those described in the main text. Specimens 1 through 3 were analyzed as nonuniform, and the characteristic vertical pattern of density variation is very apparent. This pattern was believed to be, in part, the result of washing fines from the bottom to the top of the specimen during seepage saturation resulting in denser

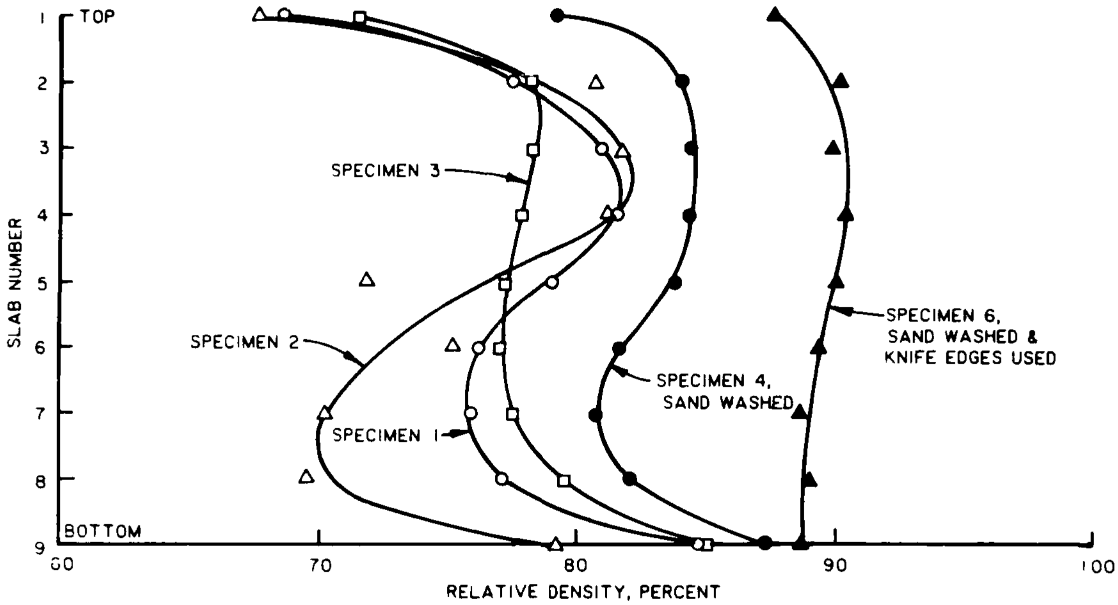


Figure D2. Vertical density patterns in early sand specimens

top layers. In specimen 4, the fines were removed from the Reid-Bedford model sand by washing and the specimen was analyzed to be more uniform than the former three. Specimen 5 was lost due to a membrane leak. In specimen 6, a set of annular "knife edges" was placed about the mold so that particles would either fall cleanly into the mold or strike the beveled surface of the knife edges and be deflected out. In this way, it was hoped that the central flow would not be disrupted by particles striking the flat top edge of the mold and deflecting into the central stream. The result of this less-disrupted flow is obvious from the analysis of specimen 6. The nonuniform vertical pattern had been effectively removed, but the relative density had become very high. The specimen seems uniform from inspection of the vertical discs (slabs), but is seen to be very nonuniform upon closer inspection of the data for the 108 elements. Even though the average densities of the vertical discs (slabs) are approximately equal, these discs are internally nonuniform. Therefore the standard deviation of all the 108 elements from the average is high and the specimen is determined to be quite nonuniform. This is shown in Table 1 (main text) where the standard deviation of the 9 discs is compared with the standard deviation of 108 elements. The computer printout sheets showing the density distribution analyses for these early tests are shown in

Figures D3 through D7. From the tabulation below, it is seen that specimens 1 to 3, which were identical in preparation technique, varied only 2.6 percent in average relative density, but had a nonuniformity measured as 8 to 9 percent relative density relative density standard deviation.

	Specimen				
	1	2	3	4	5
Standard deviation, 9 discs, % D_r	4.24	5.28	3.02	2.25	0.84
Standard deviation, 108 elements, % D_r	8.32	8.59	9.34	6.47	7.01
Posttest specimen average relative density, % D_r	78.08	75.43	77.99	83.12	89.51

5. From the analysis of these data it was determined that this procedure would not yield specimens of the required density uniformity.

Pluviation over Screens

6. Several problems with this specimen placement technique were pointed out by Casagrande when he observed the pluviation through air procedures in July 1979:

a. Material enters the mold so rapidly that air currents are created which increase nonuniformity.

b. As the distance increases from the bottom of the hopper to the top of the mold, the area of the column of falling sand contracts so much that it is possible that material was not deposited directly along the periphery of the forming specimen, but was deposited in a mound at the center and rolled into place along the periphery.

c. The height of drop was too large.

d. The plate which released the flow of sand did not do so uniformly across the area of the specimen. That side which was released first began to build up first, and the top surface of the specimen was always inclined because of the initial deposition.

7. For these reasons it was decided to pursue a dry-raining technique where the rate of material deposition was very slow relative to the former rate and where the equipment allowed a more horizontal and level top specimen surface. It was also decided to switch to Banding sand because Reid-Bedford sand with the fines removed is not a standard material.

8. To provide a more uniform surface during placement, the hopper with the open screen at the bottom was replaced by one which contained three holes

ANALYSIS OF RELATIVE DENSITY DISTRIBUTION

COLUMN

top

		1	2	3	4	5	6	7	8	9	10	11	12	
	I	71.44	81.41	69.66	74.22	66.97	78.08	76.76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	I
	II	78.00	81.29	76.93	83.53	72.80	82.24	74.44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	II
S	III	73.10	73.35	78.00	89.40	77.68	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	80.33	III
L	IV	91.17	78.65	82.82	78.87	[illegible]	79.42	80.12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	IV
A	V	89.66	78.37	82.85	69.39	84.22	82.35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	V
B	VI	65.40	71.96	64.69	85.96	79.84	[illegible]	74.11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	VI
	VII	58.38	72.16	57.07	84.09	80.82	86.29	81.13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	VII
	VIII	58.24	72.44	60.00	82.14	85.50	86.49	79.56	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	VIII
	IX	72.51	76.59	73.10	89.06	95.36	91.40	93.68	92.08	[illegible]	[illegible]	[illegible]	[illegible]	IX

bottom

AVERAGE RELATIVE DENSITY OF EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
73.21	76.25	73.01	82.40	80.44	83.84	80.55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

STANDARD DEVIATION WITHIN EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
11.03	3.66	10.78	6.50	7.01	3.80	8.18	8.49	[illegible]	[illegible]	[illegible]	[illegible]

AVERAGE RELATIVE DENSITY FOR EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
68.64	77.48	80.86	81.41	79.19	[illegible]	[illegible]	[illegible]	[illegible]

STANDARD DEVIATION WITHIN EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
6.80	3.73	5.35	3.91	6.47	[illegible]	[illegible]	[illegible]	[illegible]

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY [illegible]

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION [illegible]

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION [illegible]

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 0.48

MOMENT COEFFICIENT OF KURTOSIS A4 [illegible]

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... IX and each slab cut into segments labeled 1, 2, ... 12

Figure D3. Analysis of density distribution, initial specimen 1

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top	COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
I	58.73	66.54	75.70	77.40	78.26	61.09	59.14	[illegible].70	59.90	62.20	77.61	68.94	I
II	80.56	84.15	84.79	82.72	65.26	81.51	83.11	77.70	81.86	81.92	80.45	76.81	II
S III	86.83	83.88	83.45	86.14	67.87	80.88	79.87	79.15	81.89	87.43	83.52	80.35	III
L IV	83.91	84.88	86.69	83.63	71.25	68.92	76.68	80.36	88.11	81.06	86.06	82.68	IV
A V	79.70	77.69	68.95	69.27	72.71	77.51	53.98	63.75	81.74	66.66	83.14	72.47	V
B VI	72.17	85.94	68.13	77.60	79.37	70.92	65.65	83.55	70.33	75.12	74.39	79.38	VI
VII	61.95	80.97	72.41	74.68	88.19	77.11	70.76	59.90	56.07	60.75	69.11	71.83	VII
VIII	71.43	84.10	62.65	73.93	61.20	52.59	67.90	71.16	67.41	67.82	73.74	79.47	VIII
IX	73.71	71.20	85.49	77.00	84.65	83.95	87.99	85.26	74.20	78.57	79.50	76.26	IX
bottom													

AVERAGE RELATIVE DENSITY OF EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
74.33	79.93	76.47	78.05	74.31	72.50	71.68	74.18	[illegible]	73.91	[illegible]	76.44

STANDARD DEVIATION WITHIN EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
8.98	6.44	8.42	5.01	8.44	10.05	10.60	8.58	10.44	[illegible]	5.46	4.24

AVERAGE RELATIVE DENSITY FOR EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
67.60	80.62	81.77	81.17	71.83	75.22	70.41	69.45	79.23

STANDARD DEVIATION WITHIN EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
7.41	5.16	4.94	5.78	7.88	5.91	9.03	8.06	[illegible]

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY 8.59

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION 64.81

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION 97.22

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 = [illegible]

MOMENT COEFFICIENT OF KURTOSIS A4 2.50

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... IX
and each slab cut into segments labeled 1, 2, ... 12

Figure D4. Analysis of density distribution, initial specimen 2

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

top		COLUMN 1	2	3	4	5	6	7	8	9	10	11	12	
	I	74.47	69.24	73.33	75.22	64.32	67.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	81.92	I
	II	75.52	76.39	81.96	80.64	65.23	73.33	83.19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	II
S	III	79.38	84.08	84.58	85.10	74.79	69.26	67.32	83.71	[illegible]	[illegible]	[illegible]	[illegible]	III
L	IV	58.70	68.16	85.14	90.23	[illegible]	75.59	82.98	74.99	80.93	[illegible]	[illegible]	[illegible]	IV
A	V	77.95	88.46	92.10	83.02	73.67	81.45	78.13	77.15	75.10	[illegible]	62.76	[illegible]	V
B	VI	57.45	57.07	92.88	80.33	85.81	74.07	74.26	81.72	76.11	74.07	88.43	80.78	VI
	VII	80.94	89.84	90.65	86.96	75.99	88.29	83.61	75.67	72.06	73.01	[illegible]	55.58	VII
	VIII	85.81	85.73	87.96	89.44	81.85	90.28	89.27	[illegible]	73.42	70.19	51.87	[illegible]	VIII
	IX	83.37	87.89	87.51	92.41	92.97	92.48	71.46	[illegible]	[illegible]	84.09	[illegible]	48.85	IX
bottom														

AVERAGE RELATIVE DENSITY OF EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
74.84	78.62	86.24	84.82	76.65	79.16	80.56	78.00	77.32	77.61	[illegible]	[illegible]

STANDARD DEVIATION WITHIN EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
9.57	10.77	5.69	5.23	8.66	8.97	7.15	8.26	4.54	[illegible]	10.77	11.34

AVERAGE RELATIVE DENSITY FOR EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
73.03	78.24	78.38	77.81	77.37	76.92	77.56	79.54	85.31

STANDARD DEVIATION WITHIN EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
5.53	6.80	6.60	8.19	9.38	10.46	11.14	11.33	[illegible]

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY = 9.41

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION 66.67

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION [illegible]

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 = 0.59

MOMENT COEFFICIENT OF KURTOSIS A4 [illegible]

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... IX
and each slab cut into segments labeled 1, 2, ... 12

Figure D5. Analysis of density distribution, initial specimen 3

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

top	1	2	3	4	5	6	7	8	9	10	11	12	
I	79.47	75.74	83.87	86.26	76.88	76.12	75.52	77.13	81.[illegible]	78.20	82.09	78.72	I
II	88.14	84.36	87.17	88.53	81.57	79.12	74.54	79.64	85.93	86.19	86.17	87.61	II
S III	88.09	81.11	84.14	80.64	85.68	83.67	80.25	79.37	86.67	88.30	87.05	87.90	III
L IV	85.59	85.08	76.07	74.55	86.86	89.89	84.65	86.86	88.49	86.18	81.74	86.74	IV
A V	84.69	80.64	72.54	72.27	85.91	89.03	88.51	90.46	88.21	85.28	87.35	80.43	V
B VI	81.84	76.88	67.85	64.93	84.20	85.28	89.41	91.43	90.40	86.79	73.44	86.54	VI
VII	86.71	76.34	65.59	66.54	84.90	84.68	78.98	86.75	91.40	90.43	71.68	84.98	VII
VIII	84.16	80.40	66.79	70.24	85.98	85.89	72.74	91.09	92.60	92.01	76.73	86.20	VIII
IX	82.54	83.66	82.07	79.81	92.51	94.28	92.78	91.59	89.95	90.33	82.18	85.18	IX
bottom													

AVERAGE RELATIVE DENSITY OF EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
84.58	80.47	76.23	75.97	84.94	85.33	81.93	85.06	88.34	87.08	80.94	84.92

STANDARD DEVIATION WITHIN EACH COLUMN

1	2	3	4	5	6	7	8	9	10	11	12
2.76	3.32	7.89	7.89	3.96	5.18	6.80	[illegible]	3.1[illegible]	3.[illegible]	[illegible]	3.03

AVERAGE RELATIVE DENSITY FOR EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
79.29	84.08	84.41	84.39	83.79	81.58	80.[illegible]	82.07	[illegible]

STANDARD DEVIATION WITHIN EACH SLAB

I	II	III	IV	V	VI	VII	VIII	IX
3.30	4.21	3.20	4.50	5.90	8.48	8.47	[illegible]	[illegible]

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY [illegible]

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION [illegible]

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATIONS [illegible]

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 [illegible]

MOMENT COEFFICIENT OF KURTOSIS A4 [illegible]

NOTE 1: Units are percent relative density.

NOTE 2: Specimen was cut into slabs labeled I, II, ... [illegible]
and each slab cut into segments labeled [illegible]

Figure D6. Analysis of density distribution, initial specimen 4

ANALYSIS OF RELATIVE DENSITY REDISTRIBUTION

COLUMN

	top	1	2	3	4	5	6	7	8	9	10	11	12	
	I	90.32	90.27	89.76	88.40	83.76	81.24	84.60	80.83	92.52	93.80	[illegible]	89.30	I
	II	92.48	90.53	91.30	91.22	83.89	81.98	85.1[illegible]	92.81	94.72	94.32	91.64	88.96	II
S	III	94.87	90.02	88.75	87.28	85.10	88.87	88.94	83.23	96.2[illegible]	94.6[illegible]	92.30	87.41	III
L	IV	84.01	90.73	80.99	88.47	93.30	90.55	84.32	91.95	[illegible]	95.31	92.70	92.03	IV
A	V	83.60	87.53	77.13	81.34	92.26	89.62	91.01	94.60	96.74	96.[illegible]	92.48	98.44	V
B	VI	83.07	84.58	70.78	81.69	90.96	87.33	91.61	97.52	98.19	97.[illegible]8	90.92	97.83	VI
	VII	97.83	91.28	77.45	70.07	85.56	91.50	99.05	92.63	99.01	95.38	80.21	83.77	VII
	VIII	84.51	80.12	66.69	79.62	95.78	87.74	95.77	99.92	93.35	99.13	89.19	95.86	VIII
	IX	89.77	86.55	78.41	87.21	61.43	95.73	96.73	99.36	91.92	88.0[illegible]	93.12	97.13	IX
	bottom													

- - AVERAGE RELATIVE DENSITY OF EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
88.94	87.96	80.14	83.98	85.78	88.62	90.85	92.54	95.35	91.92	89.91	92.80

- - STANDARD DEVIATION WITHIN EACH COLUMN - -

1	2	3	4	5	6	7	8	9	10	11	12
5.12	3.50	8.03	6.16	9.58	3.86	5.15	6.28	2.32	2.87	4.92	[illegible]

- - AVERAGE RELATIVE DENSITY FOR EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII	IX
87.64	90.11	89.85	90.44	90.08	89.32	88.44	89.00	88.79

- - STANDARD DEVIATION WITHIN EACH SLAB - -

I	II	III	IV	V	VI	VII	VIII	IX
4.05	3.54	3.82	4.77	6.31	7.96	8.90	[illegible]	[illegible]

GROSS STANDARD DEVIATION, PERCENT RELATIVE DENSITY [illegible]

PERCENT OF ELEMENTS WITHIN ONE STANDARD DEVIATION [illegible]

PERCENT OF ELEMENTS WITHIN TWO STANDARD DEVIATION [illegible]

AVERAGE PERCENT WATER CONTENT OF ENTIRE SPECIMEN AFTER TEST [illegible]

AVERAGE RELATIVE DENSITY OF ENTIRE SPECIMEN AFTER TEST [illegible]

MOMENT COEFFICIENT OF SKEWNESS, A3 1.1[illegible]

MOMENT COEFFICIENT OF KURTOSIS A4 [illegible]

NOTE 1: Units are percent relative density

NOTE 2: Specimen was cut into slabs labeled I, II, ... [illegible]
and each slab cut into segments labeled 1, [illegible] 12

Figure D7. Analysis of density distribution, initial specimen 6

at 120 deg in a 1/4-in. plate. A second plate was stacked against the first and also contained three holes with identical spacing as the first. The second plate was fitted on the hopper so that it could slide against the first, and in this manner the six holes between the two plates could be aligned simultaneously by sliding the second plate, thus allowing sand in the hopper to begin feeding through all holes at the same instant in time. This mechanism is identical in principle to that used on salt and talcum powder containers where a twist of the cap aligns and opens all holes simultaneously.

9. The three open holes at the bottom of the hopper discharged sand symmetrically onto a feeder plate containing a hexagonal pattern of holes. Under this plate was a series of 11 uniform perforated plates or screens to disperse the flow of sand. Two rates of deposition were obtained using two feeder hole sizes. The two rates were such that a specimen could be deposited in 9 or 15 min, which was 12 and 20 times slower, respectively, than the initial rate. The hole size for 15-min deposition was determined to be the minimum for this sand since smaller holes would not allow continuous flow, but instead would clog and stop feeding. The 9-min plate was the one used predominantly in the early study. A photograph of the hopper bottom and screens is shown in Figure D8.

10. It was decided to insert the deposition mechanism into the mold and remove it at the rate required to maintain a constant height of drop from the bottom screen to the sand surface. A cylindrical thin metal sleeve was wrapped around the screens in such a manner that the mechanism would just fit down inside the mold. The purpose of the sleeve was to retain material on the screens. Without the sleeve, sand particles would bounce off the edges of the

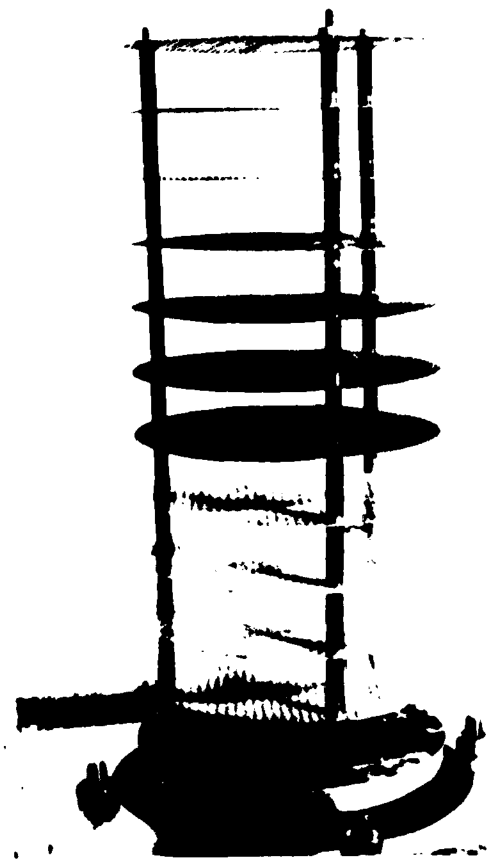


Figure D8. Modified hopper showing screens

screens, resulting in a deficiency of material around the periphery of the forming specimen and, consequently, the buildup of a high mound in the center.

11. It was determined that average specimen density was very sensitive to drop height through air for this sand and this device, as can be seen in Figure D9. From this figure, it is apparent that a small change in drop height will result in a significant change in the deposited density and the importance of maintaining a constant drop height and a level specimen surface becomes apparent. Of critical importance, also, is the fact that the densities of interest (40 to 70 percent) are on the steepest portion of the curve.

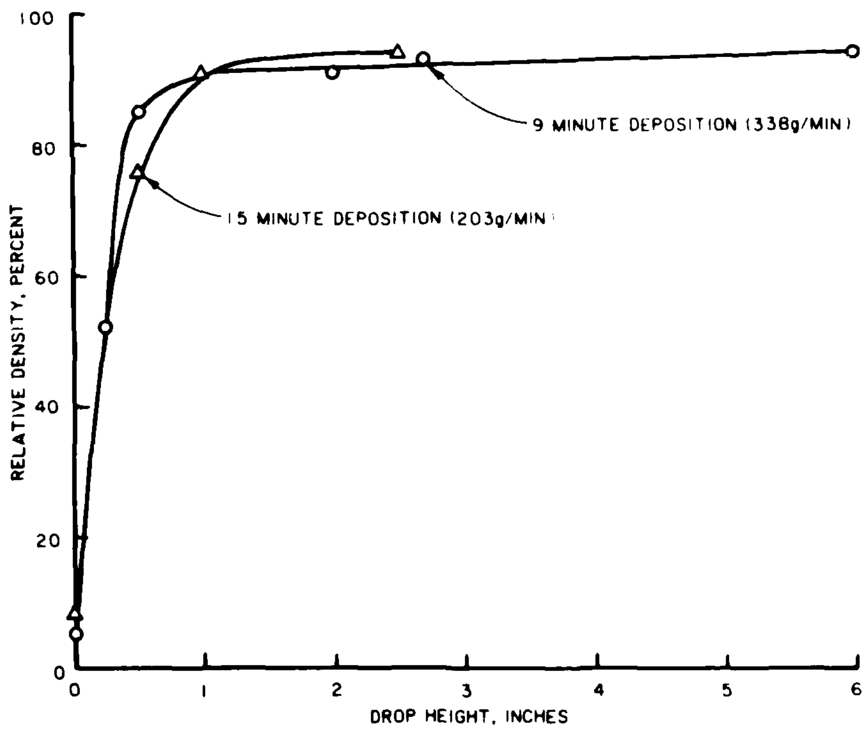


Figure D9. Relative density versus drop height

12. In spite of the rather elaborate placement mechanism, the top surface did not build up level and, from Figure D10, it was reasoned that the resulting specimen would not be uniform. To observe the top surface of the specimen, deposition was performed in a transparent lucite tube of the same inner diameter (4 in.) as the specimen. The deposition procedure with the surrounding sleeve initially yielded a specimen with a mound in the center about 1/4 to 3/8 in. high as shown in Figure D11. It was reasoned that this mound height could be reduced by systematically stopping up holes in the screens as observation dictated and, in this manner, allow the buildup of a

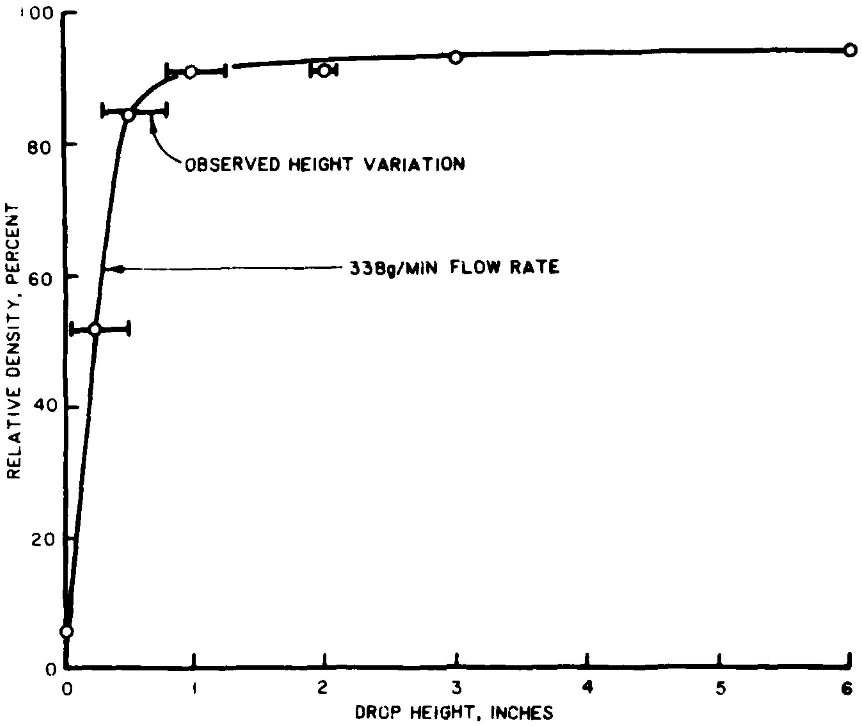


Figure D10. Relative density versus drop height showing observed mound height

Figure D11. Typical mound height inside mold level and horizontally proceeding top surface. This procedure did not eliminate the mound on the specimen top surface and the trial-and-error procedure of logically closing holes only moved the mound around on the top surface from one location to another. This phenomenon was an unavoidable consequence of particulates falling through uniform screens. An exhibit at the Chicago Museum of Science and Industry, called a Dalton's board, shows uniform spheres being dropped through a maze of quincuncial spaced pegs and being caught in a series of bins underneath the location where they were released, but some will deviate and arrive in a bin off to the side of the location where they were released. It can be mathematically shown that the mound created by the spheres is a normal distribution curve. Analogously, rounded sand grains falling from an orifice through uniform screens will invariably create this kind of mound and, therefore, it is statistically impossible to build a horizontal and level surface using this procedure. Therefore this procedure was abandoned in favor of one where pluviation through water would be employed. This procedure is described in Part II of the main text.

APPENDIX E

CHRONOLOGY OF EVENTS DURING THE PROJECT

April-June 1974

1. The writer spent three months at Harvard University assisting in the completion of a research project by Franklin Rendon under the direction of Professor Arthur Casagrande. The project concerned investigating density redistribution in sand specimens subjected to cyclic gyratory and cyclic simple shear. While at Harvard, the writer observed the technique of specimen freezing, dissection, and water content analysis to investigate density redistribution. Equipment for performing a similar study in cyclic triaxial test specimens was discussed with Professor Casagrande.

November 1978

2. A proposed plan of testing to evaluate the extent of water content redistribution in cyclic triaxial test specimens was prepared at WES and sent to Professor Casagrande. Concurrent with the preparation of the plan of testing, equipment was being assembled to perform the required laboratory tests.

February 1979

3. Professor Casagrande commented on the proposed plan of tests and laboratory equipment. His principal concerns were with (a) achieving a uniformly advancing freezing front in the test specimen to prevent water entrapment and resulting density disturbance and (b) being able to handle frozen elements such that their water content did not increase due to condensation from the environment.

March 1979

4. The OCE Board of Consultants, including Professor Casagrande, listened to the proposal of tests and procedures for the water content redistribution study. The recommendation was that dry pluviation be used as a first attempt at specimen placement and that nonlubricated end caps be used for the tests. Preliminary data were presented which showed that the freezing front proceeded approximately horizontal for the freezing system proposed and that frozen elements in thermal equilibrium with the environment lose water content

due to ice sublimation in an environment with less than 100 percent relative humidity rather than gain water content due to condensation.

April 1979

5. An attempt was made to freeze the first specimen inside a pressurized triaxial chamber filled with a solution of water and ethylene glycol. The attempt failed due to a too dilute solution of ethylene glycol in the chamber water and thermal stratification in the chamber fluid. The tendency for thermal stratification prevented a temperature at the top of the specimen cold enough to allow freezing. During the latter part of this month, these problems were corrected and specimens were successfully frozen and dissected.

May 1979

6. Three specimens of Reid-Bedford model sand were placed, frozen, and analyzed for density uniformity. These results were sent to Professor Casagrande for evaluation.

June 1979

7. Professor Casagrande determined that these specimens were not uniform enough to proceed with the water content redistribution investigation. He proposed to visit WES in August and observe the specimen placement and freezing technique.

July 1979

8. Two additional tests were performed in an attempt to improve specimen density uniformity before the visit of Professor Casagrande. A collar to improve the flow characteristics of sand being rained into the mold was added and the sand was washed clean of material finer than the No. 200 sieve to eliminate the problem of migration of fines during saturation. These changes did not substantially improve density uniformity.

August 1979

9. Professor Casagrande, Mr. Stanley Wilson, Professor Raul Marsal, and Dr. Gonzalo Castro observed the placement of specimens by dry pluviation, the experimental procedure including the freezing technique and the dissection technique, inside the environmental room. The opinion of these consultants was that the major sources of density inhomogeneity were in the construction of the specimen, notably the flow rate was concluded to be too fast and the height of drop too great. The experimental procedure, including the freezing technique and the dissection procedure, was judged to be suitable and correct. It was proposed to change from Reid-Bedford sand to Banding sand to eliminate the problem of migration of fines since Banding sand contained no material finer than the No. 270 sieve. It was suggested by Professor Casagrande that the sublimation study be repeated and a study performed to determine the effect of time exposure of dissected elements in the environmental room.

September 1979

10. Design and fabrication of a new slow flow rainer to correct the problems observed by the consultants in August began during this period.

December 1979

11. The sublimation and time exposure experiments were completed and the results showed that the effect of sublimation was negligible for the times of exposure of the soil elements of this study. These results were sent to Professor Casagrande.

January-February 1980

12. Fabrication of the new rainer was completed and systematic experiments were begun to develop a procedure to place a specimen by raining the material through uniform screens to disperse the flow uniformly. All of the problems pointed out during the visit of August 1979 were addressed by the new rainer.

13. Pluviation through screens did not yield a specimen with a level

deposited surface in spite of systematically trying different screen sizes and screen spacings. Pluviation through screens always resulted in a mound in the center of the specimen.

March 1980

14. Since pluviation through uniform screens always resulted in a mound, the decision was made to try altering the uniformity of the screen (by stopping up holes at logical experimentally suggested locations) to eliminate the center mound. This resulted only in moving the mound to different locations in the mold or replacing a single mound with multiple mounds. These experiments did not result in a level specimen surface. At this time, it was observed that pluviation through screens is a variation of the random walk problem of probability methods and could never be made to yield a level specimen surface. With this observation and the knowledge that density in Banding sand is extremely sensitive to drop height, it was concluded that this method would not yield specimens uniform in density. Therefore this procedure was abandoned.

15. Anticipating that Professor Casagrande would be at WES on 22 April, a crash program was initiated to build a uniform specimen and have it tested before that time. It was decided that the next attempt at placing uniform specimens would be by the technique of pluviation through water.

April 1980

16. Several procedures were tried in an attempt to place a uniform specimen. A specimen was vibrated continuously and the sand was pluviated through water; the result was a severe linear density variation with depth. A technique was employed where specimens were prepared by pluviating layers through water and densifying each layer by impacting a falling weight against a frame connected to the triaxial baseplate to which the specimen and mold were fastened. Two specimens were prepared using this technique. One specimen was saturated, consolidated, and used as a control; the other was cyclically loaded to 75 percent pore pressure response and the density distribution analysis was presented to Professor Casagrande on 22 April. Upon examination of these data, Professor Casagrande judged that these specimens were not of

sufficient uniformity that density redistribution could be identified. However, several important new directions came from discussions during the conferences of this visit. From the data presented to the consultants, it was determined that there appeared to be a dense zone around the periphery of specimens deposited by pluviation through water and a fairly uniform interior. The statement was made by one of the attendees of the meeting that a uniform specimen was inside the overall specimen and the required uniformity might be accomplished by removing the outer periphery of a specimen pluviated through water.

17. Professor Casagrande suggested that density be presented as percent relative density and agreed that specimens with an initial standard deviation of the same order as that achieved in the Harvard gyratory shear study (which was about 2.5 percent relative density about the average) would be uniform enough to proceed with the investigation and obtain meaningful results. This was the last time Professor Casagrande visited WES.

May-September 1980

18. In the period which followed, it was determined that there was indeed a very dense 1/2-in. crust around the outer periphery of the specimens and that this should be removed to improve density uniformity. It was determined that specimens would be built with a 1-in. oversize diameter and 1 in. would be removed from the diameter with a small metal cutting lathe inside the environmental room. It was also decided that the layers forming the specimen must be perfectly level before compaction, so a transparent lucite mold was fabricated so that the specimen could be observed and a leveling rod similar to that used at Harvard in the gyratory shear study was constructed to gently scrape the top specimen surface level.

October-December 1980

19. During this period the new equipment, including the lathe, was put into production. Flaws in equipment and procedures were discovered and corrected and systematic experiments were begun to mold specimens of the required density uniformity. A vacuum procedure was developed to remove all air from water in the mold and the material comprising the layers. The technique of

depositing sand layers into the mold in a completely submerged state with no contact with air whatsoever was developed.

January 1981

20. Experiments continued. It was determined that by using the technique of vacuum air removal, submerged material deposition, layer leveling before impact compaction, and removal of 1 in. from the diameter of the specimen and 1 in. from either end, the resulting radial uniformity was quite acceptable However, vertical uniformity was not yet acceptable and a study to achieve vertical uniformity was undertaken. By trial and analysis, it was determined that a schedule of energy application which varied logarithmically from 25 hammer blows applied to the connecting frame for the first layer to 300 blows in the last layer (and a 1-psi surcharge placed on the specimen as it was initially frozen for lathing) produced a specimen of the required uniformity at 60 percent relative density.

February 1981

21. The first specimen with the required uniformity was produced. The standard deviation was 1.67 percent relative density. The standard deviation in the second control specimen was 2.18 percent relative density. This confirmed that the procedure of placing oversize specimens by pluviation through de-aired water, densification by logarithmic energy application, freezing of the resulting oversize specimens under surcharge, and lathe removal of the outer 1/2 in. of the periphery produced specimens of the required uniformity.

March-September 1981

22. The program of testing continued. The series of cyclic and monotonic tests at 60 percent relative density was completed. Word was received that Professor Casagrande, who had been seriously ill for several months, had died on September 6, 1981.

October 1981-April 1982

23. The series of tests at approximately 70 percent relative density was completed.

April-July 1982

24. The series of tests at approximately 45 percent relative density was completed.

July-October 1982

25. A draft report describing the equipment and results was prepared.

October 1982-February 1983

26. The draft report was reviewed and it was concluded that certain tests at 40 percent relative density should be repeated for clarity. Also, specimens prepared by more normal techniques, such as moist tamping, should be examined for initial uniformity and tested. These results should be added to the final report for completeness.

April-June 1983

27. The required additional tests were performed.

October-December 1983

28. The final draft report was completed.

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