POTAMOLOGY INVESTIGATIONS

REPORT NO. 12-1

DENSITY CHANGES OF SAND CAUSED BY SAMPLING AND TESTING

SOILS INVESTIGATION

PREPARED FOR

THE PRESIDENT, MISSISSIPPI RIVER COMMISSION

CORPS OF ENGINEERS, U. S. ARMY

VICKSBURG, MISSISSIPPI

BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

JUNE 1952
# POTAMOLOGY INVESTIGATIONS REPORTS

Issued Prior To and Including This Report

<table>
<thead>
<tr>
<th>Report No.</th>
<th>Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Instructions and Outline for Potamology Investigations</td>
<td>November 1947</td>
</tr>
<tr>
<td>1-2</td>
<td>Outline of Plans for the Potamology Investigations</td>
<td>December 1947</td>
</tr>
<tr>
<td>2-1</td>
<td>Preliminary Flume Tests of Mississippi River Revetment (1st Interim Report)</td>
<td>October 1947</td>
</tr>
<tr>
<td>2-2</td>
<td>Preliminary Tests of Mississippi River Dikes, Bank Stabilization Model</td>
<td>June 1950</td>
</tr>
<tr>
<td>2-3</td>
<td>Preliminary Tests of Experimental Baffles, Bank Stabilization Model</td>
<td>September 1951</td>
</tr>
<tr>
<td>2-4</td>
<td>Preliminary Flume Tests of Mississippi River Revetment (2nd Interim Report)</td>
<td>November 1951</td>
</tr>
<tr>
<td>3-1</td>
<td>Preliminary Laboratory Tests of Sand-Asphalt Revetment</td>
<td>July 1948</td>
</tr>
<tr>
<td>5-1</td>
<td>Geological Investigation of Reid Bedford Bend Caving Banks, Mississippi River</td>
<td>July 1947</td>
</tr>
<tr>
<td>5-2</td>
<td>Field Investigation of Reid Bedford Bend Revetment, Mississippi River (3 volumes)</td>
<td>June 1948</td>
</tr>
<tr>
<td>5-3</td>
<td>Reid Bedford Bend, Mississippi River, Triaxial Tests On Sands</td>
<td>May 1950</td>
</tr>
<tr>
<td>5-4</td>
<td>Piezometer Observations at Reid Bedford Bend and Indicated Seepage Forces</td>
<td>May 1950</td>
</tr>
<tr>
<td>5-5</td>
<td>Standard Penetration Tests, Reid Bedford Bend, Mississippi River</td>
<td>May 1950</td>
</tr>
<tr>
<td>*5-6</td>
<td>Undisturbed Sand Sampling and Cone Sounding Tests, Reid Bedford Bend Revetment, Mississippi River</td>
<td>May 1951</td>
</tr>
<tr>
<td>7-1</td>
<td>Soils Investigation, Bauxippi-Wyanoke Revetment</td>
<td>June 1951</td>
</tr>
<tr>
<td>8-1</td>
<td>Haddosrable Bend, Mississippi River, Revetted Bank Failure, Soils Investigation</td>
<td>June 1950</td>
</tr>
<tr>
<td>9-1</td>
<td>Bank Caving Investigations, Kempe Bend Revetment, Mississippi River</td>
<td>November 1951</td>
</tr>
<tr>
<td>10-1</td>
<td>Preliminary Development of Instruments for the Measurement of Hydraulic Forces Acting In a Turbulent Stream</td>
<td>June 1948</td>
</tr>
<tr>
<td>10-2</td>
<td>Turbulence In the Mississippi River</td>
<td>May 1950</td>
</tr>
<tr>
<td>*10-3</td>
<td>Evaluation of Instruments for Turbulence Measurements, 1948-1949</td>
<td>March 1951</td>
</tr>
<tr>
<td>11-0</td>
<td>Resume of Conference Initiating Potamology Investigations, 11 February 1947</td>
<td>Feb 1947</td>
</tr>
<tr>
<td>11-2</td>
<td>Report of First Potamology Conference With Hydraulics Consultants, 9-10 December 1948</td>
<td>December 1948</td>
</tr>
<tr>
<td>11-3</td>
<td>Minutes of Conference on Soil Studies, Potamology Investigation, 18 April 1949</td>
<td>April 1949</td>
</tr>
<tr>
<td>11-5</td>
<td>Minutes of Conference With Soils Consultants, Stability of Mississippi River Banks, 5-8 October 1949</td>
<td>October 1949</td>
</tr>
<tr>
<td>11-6</td>
<td>Report of Conference on Potamology Investigations, 6-7 October 1949 (Volume 1, Volume 2*)</td>
<td>April 1951</td>
</tr>
<tr>
<td>11-7</td>
<td>Minutes of Conference On Soil Aspects of Potamology Program, 17-18 June 1950</td>
<td>October 1950</td>
</tr>
<tr>
<td>11-8</td>
<td>Minutes of Potamology Conference, 5 April 1951</td>
<td>April 1951</td>
</tr>
<tr>
<td>12-1</td>
<td>Density Changes of Sand Caused by Sampling and Testing</td>
<td>June 1952</td>
</tr>
<tr>
<td>13-1</td>
<td>Bank Caving Investigations, Huntington Point Revetment, Mississippi River</td>
<td>June 1952</td>
</tr>
<tr>
<td>14-1</td>
<td>Goodrich Landing Revetment, Mississippi River, Field Investigation</td>
<td>June 1952</td>
</tr>
<tr>
<td>15-1</td>
<td>Bank Caving Investigations, Free Nigger Point and Point Menoir, Mississippi River</td>
<td>May 1952</td>
</tr>
</tbody>
</table>

*Not of general informational value and hence not distributed*
CORPS OF ENGINEERS, U. S. ARMY

POTAMOLOGY INVESTIGATIONS

REPORT NO. 12-1

DENSITY CHANGES OF SAND CAUSED BY SAMPLING AND TESTING

SOILS INVESTIGATION

PREPARED FOR

THE PRESIDENT, MISSISSIPPI RIVER COMMISSION

CORPS OF ENGINEERS, U. S. ARMY

VICKSBURG, MISSISSIPPI

BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

JUNE 1952
PREFACE

The investigations outlined in this report were conducted during fiscal years 1949, 1950, and 1951. The investigations for fiscal years 1949 and 1950 were authorized by the President, Mississippi River Commission in 1st indorsements to Waterways Experiment Station letters, dated 18 May 1948 and 21 February 1949, subjects, respectively, "Special Projects for Fiscal Year 1949" and "Special Projects for Fiscal Year 1950." Additional studies were authorized in 1st indorsement to Waterways Experiment Station letter, dated 4 April 1950, subject, "Proposed Potamology Investigation Program and Budget for 1951 Fiscal Year."

Messrs. W. J. Turnbull, S. J. Johnson, W. G. Shockley, A. A. Maxwell, P. K. Garber, and R. F. Reuss, engineers of the Soils Division, Waterways Experiment Station, were actively connected with the investigation. This report was prepared by Messrs. Garber and Reuss.
CONTENTS

PREFACE ................................................................................. 1
PART I: INTRODUCTION .......................................................... 1
  Purpose of Investigation ..................................................... 1
  Scope of Tests .................................................................. 1
  Terms and Symbols ........................................................... 3
PART II: TESTING PROGRAM, RESULTS, AND CONCLUSIONS .... 5
  Testing Program ................................................................ 5
  Discussion of Results ......................................................... 8
  Conclusions ..................................................................... 14
PART III: EXPERIENCE GAINED IN ROUTINE SAMPLING AND TESTING .... 16
PART IV: RECOMMENDATIONS .................................................... 18
BIBLIOGRAPHY ........................................................................ 19

TABLE 1

PIATES 1-5

APPENDIX A: EQUIPMENT

Drill Rig ................................................................. A1
Pressure-recording Device ........................................ A1
Settlement-recording Device .................................... A2
Sampler ................................................................... A2
Test Drum ............................................................. A3
Overburden Loads .................................................... A3

APPENDIX B: TEST PROCEDURES

Placement of Test Sand .................................................. B1
Sampling Procedure ..................................................... B2
Laboratory Density Determinations .......................... B5
Other Laboratory Tests ............................................... B6
Plates B-1 - B-4
## CONTENTS (Cont'd)

### APPENDIX C: ANALYSIS OF VARIABLES AND DETAILED RESULTS OF TESTS

<table>
<thead>
<tr>
<th>Variables</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables in Equipment</td>
<td>C1</td>
</tr>
<tr>
<td>Variables in Procedure</td>
<td>C3</td>
</tr>
<tr>
<td>Density Determination</td>
<td>C5</td>
</tr>
<tr>
<td>Tables C-1 - C-4</td>
<td></td>
</tr>
<tr>
<td>Plates C-1 - C-13</td>
<td></td>
</tr>
</tbody>
</table>
DENSITY CHANGES OF SAND CAUSED BY

SAMPLING AND TESTING

PART I: INTRODUCTION

Purpose of Investigation

1. In the "undisturbed" sand sampling procedures used and developed by the Waterways Experiment Station in its exploration work, the question arose as to how much disturbance actually occurs in samples so obtained. The investigations described herein were conducted to answer that question and to provide a basis for recommended field procedures which would minimize sample disturbance. The investigations involved determination of the magnitude of the density changes occurring in sands during sampling, handling, and subsequent testing, and how these density changes are related to certain procedural, equipmental, and natural variables. This report discusses the results of the effects of the factors causing disturbance and evaluates the test methods used.

Scope of Tests

2. The three series of tests performed and the variables studied in these investigations are outlined below.

   a. First series (tests 1-1 through 1-8) included eight tests of medium sand. Variables studied were:
      (1) Initial relative density.
      (2) Inside clearance of sampler.
      (3) Rate of penetration.
b. Second series (tests 2-1 through 2-11) included eleven tests of medium sand. Variables studied were:

(1) Initial relative density.
(2) Sampler diameter.
(3) Rate of penetration.

c. Third series (tests 3-1 through 3-18) included eighteen tests: four tests of medium sand, and fourteen tests of fine sand. Variables studied were:

(1) Initial relative density.
(2) Inside clearance of sampler.

3. A major consideration throughout these investigations was the problem of distinguishing between the following types of variations in observed sample density.

a. Variations related to controlled changes in equipment or procedure, such as sampler dimensions and rate of penetration.

b. Variations related to unknown variations in initial density which can only be estimated from samples obtained by a procedure where the variations outlined in a are held constant for all tests.

c. Variations related to the human elements which are present in all tests.

The problem was further complicated by the fact that testing was begun at a time when neither field nor laboratory procedures could be standardized because of the lack of such basic data. A rather simple and inexpensive method of obtaining undisturbed sand samples was developed independently (1)* while these tests were in progress. Such standard tests as were later developed had to be modified from time to time and new standards

* Numbers in parentheses refer to the bibliography which follows the text of this report.
established to avoid certain inconsistencies as they became apparent. None of the procedures or equipment used in this investigation are common to all three series of tests. The detailed analysis of these data requires considerable descriptive matter and numerous cross references. The practical results of the tests, on the other hand, are quite simple and straightforward. The main text of this report is concerned primarily with the over-all results of the tests. The test equipment, procedures, and data are described in detail in appendices A through C hereto.

Terms and Symbols

4. Descriptive terms and corresponding symbols used in this report are defined as follows:

**Sampler dimensions**

- \( D_s \) = internal diameter of the sampler
- \( D_e \) = internal diameter of the cutting edge of sampler tube
- \( C \) = clearance, per cent = \( \frac{D_s - D_e}{D_e} \times 100 \)

**Sampling measurements**

- \( H_m \) = measured length of drive of the sampler
- \( \Delta H \) = increment of length of drive
- \( L_m \) = measured length of sample in the sampler
- \( \Delta L \) = increment of sample length
- \( SR \) = specific recovery ratio = \( \Delta L / \Delta H \)
- \( TR \) = total recovery ratio = \( L_m / H_m \)
- \( R \) = rate of penetration of the sampler
- \( PR \) = penetration resistance of the sampler
S = measured settlement of the sample

**Density measurements**

\[ \gamma_{di} = \text{average initial dry density before sampling} \]
\[ \gamma_{df} = \text{average dry density of sand in sampler} \]
\[ \Delta \gamma_d = \text{change in average dry density caused by sampling} = \gamma_{df} - \gamma_{di} \]
\[ \gamma_d \text{ max} = \text{maximum dry density obtained by a standard laboratory procedure} \]
\[ \gamma_d \text{ min} = \text{minimum dry density obtained by a standard laboratory procedure} \]
\[ RD = \text{relative density (per cent) of sand at a dry density of } \gamma_d \]

\[ RD = \frac{\gamma_d - \gamma_d \text{ min}}{\gamma_d \text{ max} - \gamma_d \text{ min}} \times \frac{\gamma_d \text{ max}}{\gamma_d} \]

**Statistical measurements**

s = standard error of estimate, a measure of scatter of data about a mean line of relationship of two variables such that the limits of variation expressed by the computed values of s include 67 per cent of the data

r = correlation coefficient, a measure of correlation such that \( r = 1.0 \) indicates a close relationship in the observed values of two variables and \( r = 0 \) indicates no relationship

**Miscellaneous**

P = surcharge load applied to the test sand
PART II: TESTING PROGRAM, RESULTS, AND CONCLUSIONS

Testing Program

Materials

5. The sands used in these studies were typical of those found in the alluvial valley of the Mississippi River. A medium sand (MR-1) was used in all tests in the first two series and in the first four tests in the third series. The equivalent grain-size distribution and grain shapes are shown on plate 1. The grain shapes have been classified as subrounded to rounded, the subrounded grains being predominant. The maximum and minimum dry densities (obtained as described in appendix B) of this sand are 111.6 and 98.0 lb per cu ft, respectively. The equivalent grain-size distribution and grain shapes of the fine sand (MR-2) used in the last 14 tests of the third series is shown on plate 2. The grain shapes have been classified as subangular to subrounded, the subrounded grains being predominant. The maximum and minimum dry densities of this sand are 102.2 and 82.8 lb per cu ft, respectively.

Equipment

6. The details of the equipment and operations used to perform these tests are described in appendix A and references (1), (2), and (3). The general equipment used, with certain variations for each test, can be described as follows: The samplers were the fixed piston type, using thin-walled seamless steel Shelby tubing. The dimensions of the samplers were varied throughout the tests. The sampler was advanced by the hydraulic unit of a truck-mounted, rotary-type drill rig. The drill rig was equipped with special devices designed to measure and record the
settlement or expansion of the sample, to maintain uniform rates of penetration, to measure pore-water pressures in the sample, and to measure and record the hydraulic pressure required to advance the sampler. The test sands were placed in a large drum set in the ground. The water level in the drum could be varied and a surcharge load could be applied to the surface of the test sand. The variations in test equipment used in each series of tests are outlined in table 1.

Procedures

7. The procedural details are described in appendix B and reference (1). The general procedure used can be described as follows. The test sand was placed in the drum at either a high or low initial density. Average initial density was computed for the entire drum on the basis of total dry weight and volume of the sand (after saturation and consolidation under the surcharge load). The sampler was advanced into the drum for 2.5 ft or until maximum capacity of the hydraulic unit was reached or until settlement of the sample became excessive. The rate of penetration was varied from test to test. The sampler then was excavated from the test drum. Mold density samples were taken during excavation to check the variation of initial density within the drum. The length of sample was carefully measured. The sample then was transported to the laboratory and the incremental distribution of density within the sample was determined, using all possible precautions to avoid additional disturbance of the sample. The average sample density was computed from the incremental densities. The variations in test procedure are outlined in table 1 for each series of tests.
Variables

8. The detailed analysis of all known variables is given in appendix C at the end of this report. The variables considered in this investigation are outlined in the following paragraphs.

9. The dimensions of the sampler, the rate of penetration, length of drive, and rate of withdrawal influence the density changes which occur during sampling and also have a pronounced effect on the cost of field sampling. Generally speaking, these two effects are opposed and when the magnitude of a given variable is changed to obtain less density change, it has a detrimental economic result. For example, density change decreases as the length of drive is decreased but the unit cost of sampling per foot of sample is materially increased. It was necessary therefore to weigh the effects of these variables very carefully to obtain the most desirable value of each from both the density change and the economic considerations. Standardized values of these variables can be specified within practical tolerances, having once obtained the most desirable value of each; the secondary effect of variations within the specified tolerances was also considered in this investigation.

10. The initial average dry density of the test sand can be computed from the over-all volume and dry weight. The true initial density varies both vertically and horizontally. In these tests the vertical variation was estimated by placing the sand in incremental layers of known weight and measuring the increase in height of the test material. The effect of compaction of any given layer on all previous layers was unknown, however, and the final variation of density caused by consolidation under the surcharge load could not be estimated. The only recourse was to obtain check
densities by a sampling procedure wherein the equipmental and procedural variables were held constant. This was by no means a perfect solution, since the density check procedure caused a certain amount of density change which in some cases exceeded that caused by the sampling procedure being investigated.

11. The additional density change caused by the necessary handling and transportation of the sample and the incremental density determination procedures could not be separated from that caused by sampling or from the initial variation in density in the actual test results. This additional density change was estimated on the basis of results of special tests wherein sand was placed in sampling tubes at known densities and then subjected to the same treatment as the test samples.

**Discussion of Results**

12. The detailed results of the sampling tests and related special tests are given in appendix C. The sampling test results also are outlined in table 1.

**Error evaluation tests**

13. Measurements of sample tube diameters and cutting edges were made to determine the variations in these dimensions when certain tolerances were specified. The average values of these dimensions tend to be slightly smaller than the specified value but the variation about the mean is very small, being equal to a standard deviation of ±0.002 in. for an average value of inside diameter equal to 2.997 in. and ±0.17 per cent for an average clearance of 0.85 per cent. The sample density is computed on the basis of the assumption that all tubes have diameters equal to the
specified diameter, thus causing a small variable error which tends to result in computed densities slightly in excess of true sample densities. It was also found that any given cross section of the tube tends to be slightly oval, having a maximum diameter which exceeds the minimum by an average value of 0.007 in.

14. Measurements of weight and length of two sample increments were made by five different operators to evaluate variations in incremental density caused by the human variation in laboratory procedures. The results of these tests are given in appendix C. The maximum differences in weight, length, and computed density of the increments were 0.2 gm, 0.035 cm, and 0.5 lb per cu ft, respectively.

15. Eight sample tubes were filled with sand at known densities and the incremental densities determined by two procedures. The procedures used are discussed in detail in appendix B. Briefly, they are as follow: In the cup auger method the sand is removed from the tube with a small auger in 2- or 3-in. increments, while in the standard method the tube and sample are cut into 3-in. increments on a band saw; incremental dry densities are then computed on the basis of the weights and volumes of sample increments so obtained. The results of these tests are given in appendix C. The standard deviation of incremental densities was large, being equal to +2.3 lb per cu ft for the cup auger method and +2.1 lb per cu ft for the standard method. These deviations tend to be compensating when all increments in any given tube are considered. The resulting error in over-all average density was in the order of 0.8 lb per cu ft for the cup auger method. The resulting error in average density by the standard method was 0.4 lb per cu ft. All possible
precautions were taken to minimize procedural effects and errors. The corresponding variations in routine test results are probably in excess of those described above, as will be discussed later.

Special measurements

16. Penetration resistance was recorded in the third series of tests. The results are shown on plate 3 and table 1. Resistance appears to increase at any given depth of sampler penetration with increasing grain size, density, and sampler clearance. The shape of the penetration resistance diagram in the case of dense sands indicates that after an initial build-up to point A (see plate 3) resistance is proportional to depth of penetration to point B, beyond which resistance increases more rapidly. The final increase in pressure probably indicates "pile action" by the sampler and sample and, consequently, reduced recovery of sample. The fact that the return portion of the diagram, which was recorded as the pressure was released, is not horizontal indicates that the drill rig had been raised during sampling.

17. Pore-water pressures were measured at the face of the sampler piston in the last two tests of the third series. No pressure was recorded during the first foot of drive, a pressure of 0.75-in. mercury was obtained during the second foot of drive, and a vacuum of 1.25-in. mercury was obtained during the last half-foot. This final vacuum corresponds to the "pile action" recorded on the penetration resistance diagram and also indicates that poor recovery is obtained during this portion of the drive. A vacuum of 7-in. mercury was obtained during withdrawal. This vacuum is probably the result of reduced pressures created during the withdrawal in the test sand near the lower end of the sampler.
18. Continuous records of settlement were obtained in all tests of the second and third series. The settlements so obtained were somewhat in error because of the movement of the drill rig during sampling and friction in the settlement-recording apparatus. The total recorded settlement tended to be in excess of direct measurements made on the sampling tube and the drill rig in the case of dense samples. It is reasonable to assume that the incremental settlement for any drive is also excessive and the incremental length (ΔL) and specific recovery ratio (ΔL/ΔH) computed therefrom is too low. The specific recovery ratios do indicate certain trends, however. Average results of duplicate tests in the third series performed on the fine sand (MR-2) are shown on plate 4. These results indicate that the best recoveries are obtained with samplers having clearances of 0.25 and 0.50 per cent for sampler penetrations as large as 2 ft. A clearance of 1.0 per cent results in increasingly poor recovery after 1.0 to 1.5 ft of penetration. Retention of the sample in the sampler during withdrawal from a bore hole depends, in part, upon the sampler clearance. A clearance of 0.50 per cent appears, therefore, to be the most satisfactory from the standpoint of both total recovery and retention.

19. Mold density samples were taken of the test material during excavation of the sampling tubes in each test in the second and third series. The distribution of incremental mold densities so obtained was quite erratic, particularly in the case of the dense tests where the mold samples were very difficult to obtain. The overburden load was only 500 lb per sq ft in the second test series and did not cause much consolidation of the test material. Therefore, the average density computed from
over-all weight and volume of sand in the drum was assumed to be more representative of initial soil conditions than the mold density. The overburden load of 2500 lb per sq ft in the third test series caused considerable consolidation, particularly in the loose sands. Average mold densities were used to compute density changes when the mold densities indicated higher densities than those computed from the total weight and volume of test material.

**Density changes**

20. The primary criterion for accurate sampling of sands is the change in density caused by sampling. Low recovery ratios can indicate inefficient sampling, but do not necessarily reflect detrimental changes in density. Incremental densities were measured in each sample of the second and third test series in an attempt to evaluate exactly when and why detrimental density changes occur. However, determination of incremental sample density was found to be subject to an inherent error which could vary within rather wide limits and, as previously discussed, variation of true initial density in the soil being sampled could not be determined satisfactorily. Average initial drum densities and final sample densities were subject to considerably less variation than the incremental values of each because of the compensating effect of the errors in the incremental values. The following discussion of density changes is restricted to changes in average densities.

21. The average density changes obtained in all three series of tests are illustrated on plate 5. The change in density versus initial density is plotted on figure 1 of plate 5. The greatest density changes were obtained in the first series using the medium sand MR-1. The
samples were taken with 2.875-in.-diameter samplers having comparatively large clearances. High rates of penetration, depths of penetration equal to 2 to 2.3 ft, and no surcharge load were used, as outlined in table 1. The same sand was used in the second series. The clearance was reduced to 0.50 per cent and penetration was stopped when settlements appeared to be excessive. The resulting disturbance was much less than in the first series. The difference in results obtained with 2.875-in.- and 5.010-in.-diameter samples was slight. No trends exist in the density changes obtained in the second series which can be attributed to controlled variations in equipment or procedures.

22. A fine sand was used in the third series and samples were taken with 3.00-in.-diameter samplers having variable clearances and using a constant rate of penetration. The average density changes are of the same order of magnitude as in the second series of tests. No trends exist in the density changes which can be attributed to variations in sampler clearance. In comparison with the second test series, the greater lengths of drive in the third series appear to cause greater disturbance of the loose samples. Statistical correlations have been made of the results of the second and third series. The results of these correlations appear to be reasonable even though based on limited data. The scatter of the data about the line of regression as measured by standard error of estimate s is in the order of ±0.5 to ±0.7 lb per cu ft. This scatter corresponds to the average density changes caused by laboratory density determination procedures as discussed in paragraph 15. It seems reasonable to assume that the scatter obtained in the second and third test series is caused primarily by the inherent error in laboratory
procedures and is large enough to mask any density changes caused by controlled variations in sampling equipment or procedures.

23. The results of all tests have been plotted on figure 2 of plate 5 as change in relative density versus initial relative density. The combined effects of sampling and testing tended to cause a decrease in average relative density for initial relative densities greater than about 77 per cent, and an increase in relative density for lesser initial values in the second and third series. The scatter, expressed as a standard error of estimate \( s \), amounted to \( +3.5 \) per cent (in terms of relative density). The change in average relative density is large (10\% to 15\%) at extremely high and low values of initial relative density. The change is not large enough to prevent detection of these low or high densities by sampling procedures, however, as shown by figure 3 of plate 5 on which final relative density is related to initial relative density.

Conclusions

24. The following conclusions are justified within the limitations of the test data:

a. The average change in density of a sand caused by sampling and testing is controlled by the initial density of the sand. The sands tend to decrease in density (expand) during sampling at initial relative densities greater than about 77 per cent and increase in density (contract) at lesser initial densities.

b. The average change in density is not sufficient to prohibit detection of low or high initial densities where such densities exist in nature.

c. The greatest single factor causing variation about this observed trend in density change is the inherent variation in laboratory density determination procedure and is
sufficient in most cases to mask the effect of controlled equipmental or procedural variables, such as tube diameter and rate of penetration. This factor causes a deviation amounting to $\pm 0.7$ lb per cu ft for average tube densities and as much as $\pm 2.3$ lb per cu ft for incremental densities (expressed as a standard deviation) even for carefully performed procedures.

d. A clearance of 1.00 per cent combined with lengths of drive in excess of 2 ft causes excessive disturbance of the medium sand.

e. Clearances of 0.50 and 0.25 per cent tend to give better recovery of fine sand than a clearance of 1.00 per cent.

f. An increase in density, grain size, and/or clearance causes an increase in the penetration resistance of the sampler.

g. Normal variations in diameter and ovality of sampling tubes are too small to have an appreciable effect on density during sampling and testing.
PART III: EXPERIENCE GAINED IN ROUTINE
SAMPLING AND TESTING

25. The major portion of field sampling and testing in the Lower Mississippi Alluvial Valley has been concerned with sands similar to the fine sand, MR-2, used in this investigation. Three-in.-diameter samplers having clearances of about 1.00 per cent have been used successfully to obtain samples up to 2.5 ft in length. Total recovery ratios (1) have averaged approximately 0.96, indicating that the samples may be slightly overdriven, the ideal recovery ratio for 1.0 per cent clearance being 0.98. The relative densities of these samples normally are between 60 to 80 per cent (4) falling in the range where density changes caused by sampling are very small.

26. Medium sands corresponding to test sand MR-1 are found at depth in the Lower Mississippi Valley. The relative densities of these sands normally vary between 70 to 90 per cent. The combined effects of density, grain size, and overburden pressures cause high penetration resistances which tend to exceed the capacity of the drill rigs for sample lengths greater than 1.0 to 1.5 ft. This reduced length is probably desirable, since the foregoing test results indicate that greater lengths result in excessive disturbance. Sampler tubing lighter than 16 gage tends to collapse during sampling of these soils.

27. Coarse sands and gravels are encountered at depth in the valley but satisfactory samples which can be considered undisturbed have not been obtained. Sixteen-gage tubing almost invariably collapses during sampling of these materials, and the samples contained in undamaged tubing show evidence of disturbance. This disturbance probably is caused by the
movement of the very coarse grains at the cutting edge of the tube.

28. The rate of penetration and withdrawal of the sampler were controlled manually during the early stages of field sampling. Occasionally samples were obtained which contained large voids and open channels, or had large settlements after they had been shipped to the laboratory (7). It was believed that these disturbances were caused by the vacuum developed during penetration and withdrawal. The rate of penetration and withdrawal was arbitrarily standardized at approximately 0.10 ft per sec and held constant by means of a flow-control valve on the hydraulic unit of all drill rigs. No cavities or excessive settlements have been observed since the above-mentioned rate was established.

29. Continuous sampling in a bore hole results in extremely low sample densities (4). This reduction probably is caused by a disturbance resulting from the vacuum created by the withdrawal of the previous sample.

30. The stratification of all sands in the Mississippi River Valley is quite complex, strata thicknesses in excess of 1 ft being rare. Initial strata densities, where such are desired, can only be obtained from incremental density determinations rather than from over-all sample densities. The standard deviation of incremental densities caused by variations in routine laboratory density determination procedures appears to be in the order of +2.8 lb per cu ft (4).
PART IV: RECOMMENDATIONS

31. The specifications for routine sampling and testing as now used appear to be satisfactory for the fine sands encountered in the alluvial valley of the Lower Mississippi River. The clearance of the samplers should be reduced to 0.50 per cent to reduce the disturbance of the medium sands.

32. Samples should not be taken at closer intervals than 5-ft centers in a bore hole (measured vertically).

33. A very slow rate of drive and withdrawal (0.1 ft per sec) should be used to minimize sample disturbance from this procedure.

34. The length of drive should be reduced to 1.5 ft when sampling in deposits containing sands having relative densities less than 50 per cent, to prevent undue disturbance of the sample.
(1) Undisturbed Sand Sampling Below the Water Table. Waterways Experiment Station, Bulletin No. 35, Vicksburg, Miss., June 1950.


(4) Summary Report, Soils Phase of Potamology Investigations to end of Fiscal Year 1952. Waterways Experiment Station (to be published).

(5) Hvorslev, M. Juul, Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes. Vicksburg, Miss., Waterways Experiment Station, 1948.


(7) Bank Caving Investigations, Morville Revetment, Mississippi River. Waterways Experiment Station, Technical Memorandum No. 3-318. Vicksburg, Miss., September 1950.
Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (Ft)</th>
<th>Initial Density (Lf/Cu ft)</th>
<th>Change in Density (Lt/Cu ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.000</td>
<td>0.000</td>
<td>Sample removed from top of sample and placed in bottom of sample.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.000</td>
<td>0.000</td>
<td>Sample removed from bottom of sample and placed in top of sample.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.000</td>
<td>0.000</td>
<td>Sample removed from middle of sample and placed in middle of sample.</td>
</tr>
</tbody>
</table>

---

**Table 2**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density (Lf/Cu ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.000</td>
<td>Density determined after saturation.</td>
</tr>
<tr>
<td>2</td>
<td>1.000</td>
<td>Density determined after saturation.</td>
</tr>
<tr>
<td>3</td>
<td>1.000</td>
<td>Density determined after saturation.</td>
</tr>
</tbody>
</table>
Table 1

<table>
<thead>
<tr>
<th>Density Determinations</th>
<th>Density Treatments</th>
<th>Density Unit Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample collected from</td>
<td>Laboratory testing</td>
<td>In situ testing at depth</td>
</tr>
<tr>
<td>Sample tested for</td>
<td>Sample taken to determine</td>
<td>Sample taken to determine</td>
</tr>
<tr>
<td>weight and moisture</td>
<td>density and porosity</td>
<td>density and porosity</td>
</tr>
</tbody>
</table>

Note: The density of the sample was determined by the procedure outlined above.

Test results of this kind are less accurate than those from the field, and should not be given equal consideration.
SHAPES BETWEEN U.S. SIEVE SIZES 20-25

SHAPES BETWEEN U.S. SIEVE SIZES 25-30

SHAPES BETWEEN U.S. SIEVE SIZES 35-40

SHAPES BETWEEN U.S. SIEVE SIZES 40-45

EQUIVALENT GRAIN SIZE DISTRIBUTION AND GRAIN SHAPES
MEDIUM SAND MR-1

NOTE: MAGNIFICATION VARIED TO OBTAIN SAME GRAIN SIZE.
SHAPE BETWEEN U.S. SIEVE SIZES 70-80

SHAPE BETWEEN U.S. SIEVE SIZES 80-100

SHAPE BETWEEN U.S. SIEVE SIZES 100-120

SHAPE BETWEEN U.S. SIEVE SIZES 120-140

GRAIN SIZE DISTRIBUTION AND GRAIN SHAPES

FINE SAND MR-2

NOTE: MAGNIFICATION VARIED TO OBTAIN SAME GRAIN SIZE.
NOTE: HORIZONTAL AND VERTICAL SCALES AS SHOWN.
NOTE: POINTS SHOWN ARE AVERAGES OF DUPLICATE TESTS.
3-INCH DIAMETER SAMPLER.
RATE OF PENETRATION = 0.093 FT/SEC.

COMPARISON OF SPECIFIC RECOVERY RATIOS
FINE SAND
FIG 1 - CHANGE IN DENSITY VS INITIAL DRY DENSITY

FIG 2 - CHANGE IN RELATIVE DENSITY VS INITIAL RELATIVE DENSITY

FIG 3 - FINAL RELATIVE DENSITY VS INITIAL RELATIVE DENSITY

LEGEND
- SERIES I (MR-1)
- SERIES II (MR-1)
- SERIES III (MR-1)
- SERIES III (MR-2)

AVERAGE DENSITY CHANGES CAUSED BY SAMPLING
SERIES I, II, & III
APPENDIX A: EQUIPMENT

Drill Rig

1. A truck-mounted, rotary-type drill rig was used to push the samplers into the sand. The frame of the rig was held down by screw anchors. The hydraulic system of the rig was capable of exerting a drive force of approximately 8000 lb on the sampler for a length of drive of 2-1/2 ft. A general view of the drill rig and associated equipment is shown on plate A-1.

2. In the first and second series of tests the rate of penetration of the sampler varied during the drive. The drill rig used in the third series was equipped with a constant-volume, flow-control valve to maintain a uniform rate of penetration, regardless of the change in resistance to penetration. This valve was connected into the oil-feed lines between the oil pump and the hydraulic drive on the drill rig.

Pressure-recording Device

3. A pressure-recording device was used in the third series of tests to measure and record the pressure applied to the sampler during the drive. This device, shown on plate A-2, was connected to the hydraulic system of the drill rig. The recording drum was connected to the drill rod by means of a string and pulley arrangement and pressures were measured by means of a piston and calibrated spring. Oil pressure in the hydraulic system of the drill rig acted on the piston. Movement of the piston was resisted by the calibrated spring. The deflection of the spring was recorded and converted into pounds per square inch; a
continuous record of penetration resistance versus length of drive was obtained in this manner. Calibrated springs with different total capacities were used (240 and 800 psi, respectively) for the loose and dense states of density.

**Settlement-recording Device**

4. A special device was used to record the change in sample length during the drive. This device, shown on plate A-3, consists of a rectangular settlement board attached securely to the upper part of the drill rod. A recording pencil is held against the settlement board by means of a bracket attached to the settlement rod. The settlement rod is connected to a plate resting on top of the sand directly below the sampler piston. The settlement board moves downward as the drive progresses and the pencil records the length of drive with a vertical line. The bracket holding the pencil is so constructed that any movement of the settlement disk will cause a horizontal movement of the pencil. The rate of vertical movement of the disk to the horizontal movement of the pencil is 1:4. A vertical recorded line indicates no decrease or increase in the length of sample. A line to the right of the vertical indicates a decrease in sample length (settlement) and a line to the left an increase in sample length (expansion).

**Sampler**

5. Piston-type samplers similar to the one shown on plate A-4 were used in these investigations. The sampler consists of three principal parts; the sampler head and tube, the piston, and the settlement plate.
Three rods are required to operate the separate parts. The force required to drive the sampler is transmitted through the outer rod (drill rod). A 1/2-in.-diameter rod is attached to the piston. The piston rod clamp, shown on plate A-3, holds the piston stationary while the sample tube is being pushed into the sand. The settlement rod of 1/8-in. diameter operates inside of the piston rod and is connected to the settlement plate.

6. The sampler used in the last two tests in the third series was modified slightly to permit the measurement of pore pressures during sampling. The piston was drilled and one end of a plastic tube was set flush with the face of the piston. The other end of the tube was connected to a compound gage. The settlement plate and rod were removed and a solid piston rod was used to prevent any loss of pressure.

Test Drum

7. A heavy steel drum, 2-1/2 ft in diameter and 6 ft deep, was used in these tests; the top of the drum was set flush with the ground surface. Three drainage pipes on the outside of the drum were connected to openings in the bottom of the drum. The water level in the drum was raised or lowered by means of these pipes.

Overburden Loads

8. Overburden loads were applied to the test sand in both the second and third series of tests. A steel cover plate approximately 3/4 in. thick was placed on top of the sand. In the second series of tests the overburden load of approximately 600 lb per sq ft was applied
by means of lead weights. In the third series of tests an overburden load of 2500 lb per sq ft was used. This overburden load was applied by means of hydraulic jacks acting against two crossbeams. The steel cover plate and hydraulic jacks used in the third series are shown on plate A-5.
GENERAL VIEW OF SITE AND TEST EQUIPMENT
PRESSURE RECORDING DEVICE

1. CALIBRATED SPRING  
2. RECORDING DRUM  
3. DRILL ROD

PLATE A-2
SETTLEMENT RECORDING DEVICE

1. SETTLEMENT BOARD  
2. SETTLEMENT BOARD CLAMP  
3. SETTLEMENT ROD  
4. PISTON ROD CLAMP
START OF SAMPLING OPERATION

1. STEEL COVER PLATE.
2. DRILLING MUD.
3. HYDRAULIC JACKS FOR APPLYING SURCHARGE LOAD
4. DRAINAGEPIPES FROM BOTTOM OF BARREL.
5. SAMPLERTUBE.
6. DRILL ROD.

PLATE A-5
APPENDIX B: TEST PROCEDURES

Placement of Test Sand

First series

1. The sand was well mixed to insure a uniform moisture content, weighed accurately in batches of approximately 250 lb and placed in the drum in layers 6 in. thick. The sand was poured through a large funnel connected to a 4-ft length of 1-in. pipe. The bottom of the pipe was maintained approximately 5 in. above the surface of the sand. A No. 4 sieve was attached to the bottom of the pipe to check the momentum of the falling sand. The water level in the drum was raised 3 to 4 in. above the surface of the previous layer before placing a succeeding layer. Each layer was leveled and the thickness was determined.

Second and third series

2. The sand was placed at both high and low densities. The low density was obtained by pouring the dry sand through a funnel connected to a 2-ft length of 1-in. pipe. The sieve on the bottom of the pipe was replaced by a small metal plate attached at an angle of 15° with the horizontal. The distance between the metal plate and the surface of the sand was maintained constant and equal to approximately 5 in. After the sand was placed it was saturated slowly by raising the water level in the drum. The sand was poured in water and each layer was rodded with a steel rod and vibrated to obtain a high density. The density of the sand was determined after all the sand had been placed in the drum.
Sampling Procedure

First series

3. The sampler was assembled, attached to the drill rod, and lowered until the cutting edge and sampler piston touched the surface of the sand. The sampler then was pushed into the sand. No surcharge load was applied in these tests and the rate of penetration was varied for each test. Four drums of test sand were prepared. Two samples were obtained from each drum as follows: samples 1-1 and 1-2, 1-3 and 1-4, 1-5 and 1-6, 1-7 and 1-8. Samples 1-2 and 1-4 were taken from the bottom portion of the drum and the remainder were taken from the upper portion of the drum. In either case the second sample was offset approximately 18 in. from the first sample.

4. The first four samples obtained in this series were removed by the use of a freezing process. An annular auger was used to remove the material from around the sampler to within a few inches of the bottom of the sampler tube after completion of the drive. An annular freezing chamber then was lowered around the tube. Supercooled alcohol was circulated through the freezing chamber until the bottom portion of the sample was frozen; the sampler then was withdrawn from the test drum. However, additional disturbance of the sample was believed caused by the vibrations of the auger and the washing action used to remove the material from around the sampler. Therefore it was decided to drain the test drum and to remove the samples by excavating the sand from the test drum. A metal plate was placed over the bottom of the sample tube to retain the sample in the tube during the withdrawal operation. This plate was held
securely by means of two steel rods which extended from the plate to a friction clamp attached to the top of the sample tube. All samples were transported to the laboratory in a vertical position.

**Second series**

5. The surface of the test sand was covered with an annular steel plate having a diameter slightly less than the diameter of the test drum and a hole in the center to allow the sampler to pass through. The sampler was assembled, attached to the drill rod, and lowered until the cutting edge touched the sand. The sampler then was locked in this position to prevent any downward movement while the surcharge weights were placed. The sampler was released after the weights had been placed, and allowed to rest on the surface of the sand. The settlement-recording device then was attached and adjusted and the sampler was pushed into the sand. The rate of penetration varied for each test. The drive was stopped when settlement of the sample became excessive. All samples were removed by excavating the sand from the drum and placing the metal plate assembly on the bottom of the tube as previously described. All samples were transported to the laboratory in a vertical position.

**Third series**

6. The sampling procedure was changed to conform as nearly as possible to the procedure now used to obtain undisturbed sand samples below the water table (1). After the steel surcharge plate had been placed on the surface of the test sand, the sand immediately below the center opening in the plate was excavated to a depth of approximately 5-1/2 in. A steel sleeve 6 in. long and 4-1/2 in. in diameter was inserted through the center opening in the surcharge plate and seated
firmly on the sand. The steel sleeve served to prevent the sand from caving into the hole when the surcharge load was applied. A mixture of drilling mud and sand was placed inside the sleeve (shown on plate B-1). The sampler then was assembled and attached to the drill rod and lowered into the hole until the cutting edge and settlement plate touched the surface of the sand. The sampler was locked in this position and the surcharge load was applied by means of the hydraulic jacks. The sampler was released and again placed in contact with the surface of the sand. The settlement-recording device and pressure-recording device were attached and adjusted and the sampler then was pushed into the sand. The rate of penetration was maintained constant during the progress of sampling. The same rate of penetration was used for all tests performed in this series. The sampler was pushed a distance of 2-1/2 ft, or until the maximum allowable pressure of the drill rig had been reached.

7. The sand was excavated from around the sample as previously described. The bottom portion of the tube was sealed with a perforated expanding packer, see plate B-2, rather than the metal plate previously described. Another packer was placed in the top of the tube after the sample had been removed from the drum and the measurements of length of sample obtained. The tube then was placed in a horizontal position and consolidated by means of 50 blows of a rubber hammer uniformly distributed along the surface of the tube. The tube then was transported to the laboratory in this horizontal position with no rotation about its horizontal axis permitted.

8. Samples 17 and 18 in this series were pulled directly from the test drum without prior excavation of the sand from around the sample.
Other than this these samples were treated as described above.

**Mold density samples**

9. Density samples were obtained in the second and third series of tests during the excavation of the sand from the test drum. These samples were obtained by forcing a 4-in. length of 3-in. sample tube into the sand by hand, excavating the sand from around the sample, leveling off the top and bottom of the sample, and removing it from the test drum. These samples were taken at every 6 in. of depth and were located approximately half-way between the edge of the test drum and the center of the sample tube.

**Laboratory Density Determinations**

**First series**

10. The total length of sample and total dry weight of sand were used to obtain the average sample densities.

**Second series**

11. The sand was removed in increments approximately 2 in. long and the density of each increment was determined. A special device known as a cup auger was used to remove the increments of sample from the sample tube. The cup auger assembly, shown on plate B-3, consists of a cylindrical cup auger with a diameter slightly smaller than the diameter of the sample tube. The handle of the auger is calibrated and equipped with an adjustable stop so that any desired length of sample can be removed. The surface of the sand was leveled so that a uniform measurement could be obtained. The length of increment desired was set on the handle, the auger placed in the tube and rotated until the cup had a quantity of sand
in it. The cup then was removed from the sample tube, emptied, and the procedure repeated until the desired length of sample had been obtained. It was necessary to exercise the utmost care to prevent the loss of any material as the auger was removed for emptying and the sides of the tube and auger were cleaned to remove all grains of damp sand. The weight of each sample increment was determined and the volume computed from the increment height and internal diameter of the sample tube.

Third series

12. The samples and sample tubes obtained in the third series of tests were cut into increments approximately 3 in. long by means of a band saw. After the samples were cut into sections, the amount by which the sample failed to fill each section of the tube (transverse settlement) was measured and recorded. The sample then was pushed out of the 3-in. length of sample tube, dried and weighed. The average length of the sample tube increment was determined accurately and the total volume of the increment was used to compute the density of the sand in that increment. This method of density determination, pictured on plate B-4, is now used in preference to the cup-auger method and is referred to in this report as the "standard" method of density determination.

Other Laboratory Tests

General tests

13. Maximum and minimum density and equivalent grain-size determinations were performed on the sand used in each series of tests. The maximum density was determined by pouring the dry sand into a 2- by 4-in. mold in 100-gm layers, and compacting each layer with 25 blows of a 10-lb
hammer falling 18 in. The minimum density was determined by pouring the dry sand from a constant height into a 2- by 4-in. mold in 100-gm layers. These test procedures and the advantages and disadvantages thereof are discussed in detail in reference (4) of bibliography following the main text of this report.

Special density tests

14. The cup auger method of density determination was checked during the second series of tests by density determinations performed in the laboratory on four prepared samples of sand. The dry sand was poured into the sample tube from a constant height and was saturated from the bottom. The sample was allowed to drain and incremental densities were determined using the cup auger.

15. Loose and dense samples of fine and medium sand were prepared to evaluate the standard method of density determination used in the third series of tests. The loose samples were prepared by pouring the dry sand into the tube from a constant height in accurately weighed layers of 550 gm. A piece of filter paper was placed on top of each layer. The dense samples were obtained by compacting the sand in 550-gm layers using 25 blows of a 10-lb hammer falling 18 in. A piece of filter paper was placed between each layer of sand. The loose and dense samples were saturated from the bottom, drained, and consolidated perpendicular to the long axis of the tube by means of blows, distributed uniformly along the surface of the tube, with a rubber mallet. The tube then was cut into 3-in. sections using a band saw. The location of the filter paper as placed in the tube and after cutting the tube was determined and the initial density of a section
was corrected for any density change caused by the placement and saturation procedures.
REMOVAL OF SAMPLE

1. TEST SAND
2. STEEL SLEEVE
3. DRILLING MUD
ASSEMBLED PACKER

WASHER

WING NUT

RUBBER SEALS

TOP PLATE

BOTTOM PLATE

PERFORATED EXPANDING PACKER

PLATE B-2
CUP AUGER ASSEMBLY USED IN SAND DENSITY DETERMINATIONS SECOND SERIES

PLATE B-3
CUTTING THE SAMPLE TUBE AND SAMPLE INTO INCREMENTS

REMOVING THE SAMPLE

END VIEW OF SEGMENT SHOWING TRANSVERSE SETTLEMENT

METHOD AND EQUIPMENT USED IN SAND DENSITY DETERMINATIONS

PLATE B-4
APPENDIX C: ANALYSIS OF VARIABLES AND DETAILED RESULTS OF TESTS

Variables in Equipment

1. The influence of variables in equipment on the density changes which occur during sampling are discussed in the following paragraphs.

Sampler dimensions

2. The sampler dimensions include wall thickness, internal diameter, cutting edge diameter, and per cent clearance. A detailed discussion of these variables will be found in reference (5) listed in the bibliography at the end of the main text. The following discussion is limited to the effect of these variables during sampling of sand.

3. Wall thickness. It is desirable that the sampler have a minimum wall thickness in order to reduce sample disturbance, the minimum value being controlled by the structural strength required to withstand the penetration resistance of the material being sampled. Satisfactory structural strengths have been obtained with 16-gage Shelby tubing (0.065 in.) in most sands of the Lower Mississippi Alluvial Valley for sampling depths in the order of 100 ft. At depths less than 50 ft, 18-gage tube (0.049 in.) generally is satisfactory for fine sands. All sample tubes used in this investigation were 16 gage and the effect on density change should have been constant within the permissible variation of wall thickness (+10% of wall thickness).

4. Internal diameter. The diameter of the sampler is important in its relationship to the permissible length and disturbance of the sample (5). In general, sample lengths which are equal to 5 to 10 times the internal diameter (for diameters of 2 to 3 in.) can be obtained in
cohesionless soils without undue disturbance. The disturbance tends to decrease with increasing diameter of sampler and the cost tends to increase, assuming all other variables to be constant. The larger samplers require heavier drilling equipment to overcome increased penetration resistance. Large samples are desirable from the standpoint of quantity of material obtained for further testing. The study of the effect of sampler diameter on density changes was limited in this investigation to diameters of 2.875, 3.000, and 5.010 in., the necessary sampling equipment being available for these diameters. Sand sampling methods were considerably improved (1) during the course of the investigation, and the 3.000-in.-diameter sample was found to be the most efficient for use in the field for practical economic considerations. Therefore, the latter part of the investigation was not concerned with the effect of sampler diameter on density changes, the 3-in.-diameter tubing having been more or less standardized.

5. Per cent clearance. The penetration resistance, sample recovery, sample disturbance, and retention of the sample in the sampler during withdrawal are influenced by the cutting edge diameter and corresponding per cent of clearance (5). Assuming all other variables held constant, the penetration resistance and sample disturbance will tend to diminish as the per cent clearance decreases, sample recovery will tend to increase, but the ability of the sampler to retain the sample during withdrawal will be reduced. The clearance used for routine field sand-sampling equipment has been arbitrarily standardized at 1.00 per cent. Sample recoveries have been very good in fine sand (as discussed in the main text of this report) and there has been very little indication of
any disturbance which could be attributed to the clearance. The test results obtained in this investigation are rather limited but tend to indicate that better recovery and less disturbance would be obtained with 0.50 per cent clearance.

**Dimensional variations within specified tolerances**

6. Micrometer measurements of 3-in.-diameter Shelby tubes were made and it was found that the average internal diameter of these tubes was 2.997 in. with a standard deviation of ±0.002 in. The permissible tolerances can be found in reference (6). The internal diameter of the cutting edge was specified on the basis of 1 per cent clearance and an assumed internal diameter of 3 in. The average per cent clearance, therefore, was somewhat less than 1 per cent, being equal to 0.85 per cent and having a standard deviation of ±0.17 per cent. The maximum internal diameter exceeded the minimum by an average value of 0.007 in. In view of the fact that the effect of variations in procedure on density change during sampling far exceeds that of variations in equipment, as discussed in the main text, the change in density caused by dimensional variations within the specified tolerances can be assumed to be negligible. The effect on computed density is significant, as discussed in the following paragraphs.

**Variables in Procedure**

**Rate of penetration and withdrawal**

7. The rate of penetration probably influences density changes to some extent. The results obtained in this investigation are inconclusive as concerns rate of penetration. A value of 0.093 ft per sec was used in
the last series of tests and has been used for routine field sampling since 1950. No disturbance has been observed which could be attributed specifically to rate of penetration. The important consideration probably is to use a constant rate which, for hydraulic-feed drill rigs, can be obtained with a flow-control valve similar to that used in this investigation. The effect of rate of withdrawal probably is much greater because of the vacuum so created. The rate of withdrawal was not considered in this investigation; it has been standardized for field procedures at 0.093 ft per sec. Prior to such standardization, samples occasionally were obtained which contained voids or open channels (7). The experience gained with continuous sampling (4) further substantiates the belief that the vacuum created during withdrawal may cause serious disturbance.

Length of drive

8. The length of drive has a definite influence on the amount of material entering the sampler and probably has a corresponding influence on the density changes occurring during sampling, particularly in very dense or very loose coarse sands. The total recovery ratio \( \frac{L_m}{H_m} \) can be used as a measure of efficiency of sampling, and the specific recovery ratio \( \frac{\Delta L}{\Delta H} \) can be used to determine the optimum length of drive. The total recovery ratio can be obtained quite simply from the measured length of sample and a measured length of drive. The specific recovery ratio requires special settlement-recording apparatus. A settlement-recording device was used in the second and third series of tests, the results of which are given on plates C-1 through C-6. The total settlement indicated by this device is not in agreement with that obtained by
other methods of measurement as shown in table C-1. The recorded settlements in the case of dense sands tended to be in excess of the other values because they included the effect of the upward movement of the drill rig during sampling. Considerable difficulty was experienced also with friction in the recording apparatus. Therefore, the recorded settlements cannot be used to obtain a true specific recovery ratio or the optimum length of drive. The total settlements obtained from direct sample measurements (listed on table 1 of the main text) have little variation and can seldom be consistently related to length of drive.

There are only a few general examples of the influence of length of drive on total recovery ratio and density change. For example, tests 2-2 and 2-3 compared with 3-3 and 3-4 (see table 1 of main text) indicate that poor total recovery ratios (<0.9) and excessive changes in relative density (>16.8%) are obtained in a very loose medium sand when the length of drive exceeds 1.5 to 2.0 ft. The length of drive probably is not an important consideration in sand sampling in the alluvial deposits of the Lower Mississippi Valley, since extreme values of relative density are very rare (4) and good total recovery ratios are obtained for a standardized length of drive equal to 2.5 ft (1).

**Density Determination**

9. The nature of the measured density change (increase or decrease) occurring during sampling is controlled primarily by the initial relative density of the material being sampled. The magnitude of the density change has two basic components: a change caused by the entrance and withdrawal of the sampler, and a change caused by handling, transporting,
and subsequent density determinations on the sample within the sampling tube. The variation of the first basic component about a mean value is related to certain variables in equipment and procedure, as previously discussed. The variation of the second basic component about its mean value is related to inherent variables in the procedures used and is quite substantial when compared to the variation of the first component. These two basic components are present in all test results pertaining to sample density, both in the average results discussed in the main text and in the incremental density results shown on plates C-7 through C-13.

10. An attempt was made to evaluate the magnitude and variation of density changes caused by laboratory procedures. Eight samples were prepared in the laboratory in sampler tubes by the procedures described in paragraphs 14 and 15 of appendix B. The results of these tests are shown on tables C-2 and C-3.

11. The cup auger method of density determination caused an average density increase in loose sands and a density decrease in dense sands as shown in table C-2. Sufficient tests were not performed to determine accurately the over-all average values of density changes or the standard deviation of individual average values of sample density caused by the cup auger method. However, it would appear that the average over-all density change would be in the order of +0.6 lb per cu ft for very loose sands and -1.0 lb per cu ft for dense sands, with a deviation of individual average sample density of approximately ±0.5 lb per cu ft. The standard deviation of incremental density values about the average value appears to be much greater, being about ±2.3 lb per cu ft.

12. The standard method of density determination caused an average
density decrease of -0.4 lb per cu ft for all initial densities, as shown in table C-3. The variation of individual average sample densities was in the order of +0.7 lb per cu ft. The standard deviation of incremental sample densities was +2.1 lb per cu ft.

13. An attempt was made to determine the cause of these variations in laboratory results in order that they might be reduced where possible. Computations for incremental density are based on the assumption that all tube diameters are equal to the specified diameter, when actually the true average diameter is less (2.997 for 3.000 in. specified) and has a finite standard deviation (+0.003 for 3.000 in. specified). These variations will cause the computed sample density to be lower than true sample density by -0.2 lb per cu ft, with a standard deviation of +0.2 lb per cu ft (assuming true sample density to be 100 lb per cu ft). Variation between different technicians will result in variations in measured incremental lengths, weights, and computed densities. The results of limited tests performed to evaluate this human element are shown in table C-4. The maximum difference in computed density on a given measurement of sample between five different technicians was 0.5 lb per cu ft. Other laboratory factors which might influence incremental density results are incomplete drying of the increment prior to weighing, variations between laboratory balances used to weigh the increments, and a "zero drift" on any given balance, caused by variations in incremental weights and room temperatures. The observed deviation in incremental density values probably is the result of the combined effect of many factors and therefore cannot be completely eliminated. It probably could be reduced by using the same technician(s) for all density determinations and by
requiring the technician(s) to weigh all increments on one balance which is continuously and carefully checked for accuracy. Probably it is not practical to require measurement of increment diameters, since a large number of measurements would be required because of the oval shape of the tube.

14. The deviation of incremental density about a mean value is apparent in the scatter of the test results obtained in the main investigation, as shown on plates C-7 through C-13. It is not possible to make a consistent comparison of initial and final densities of increments, since a corresponding deviation probably occurs in mold densities. In most cases the general variation of final incremental density throughout the length of sample is the same as the general variation of mold density with depth, and it would appear, therefore, that the length of drive and other variables in these tests did not cause detrimental density changes at any specific location in the samples.
### Table C-1

**LENGTH OF DRIVE AND SAMPLE MEASUREMENT IN FEET**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Drill Rod</th>
<th>Sample Tube</th>
<th>Recording Chart</th>
<th>Length of Drive</th>
<th>Length of Sample</th>
<th>Change in Length of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>2.280</td>
<td>2.190</td>
<td></td>
<td></td>
<td></td>
<td>0.090</td>
</tr>
<tr>
<td>2</td>
<td>2.280</td>
<td>2.233</td>
<td></td>
<td></td>
<td></td>
<td>0.047</td>
</tr>
<tr>
<td>3</td>
<td>2.250</td>
<td>2.220</td>
<td></td>
<td></td>
<td></td>
<td>0.030</td>
</tr>
<tr>
<td>4</td>
<td>2.280</td>
<td>2.250</td>
<td></td>
<td></td>
<td></td>
<td>0.030</td>
</tr>
<tr>
<td>5</td>
<td>2.300</td>
<td>2.300</td>
<td></td>
<td></td>
<td></td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>2.080</td>
<td>2.020</td>
<td></td>
<td></td>
<td></td>
<td>0.060</td>
</tr>
<tr>
<td>7</td>
<td>2.233</td>
<td>2.160</td>
<td></td>
<td></td>
<td></td>
<td>0.073</td>
</tr>
<tr>
<td>8</td>
<td>2.110</td>
<td>1.960</td>
<td></td>
<td></td>
<td></td>
<td>0.150</td>
</tr>
</tbody>
</table>

**2-1**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Drill Rod</th>
<th>Sample Tube</th>
<th>Recording Chart</th>
<th>Length of Drive</th>
<th>Length of Sample</th>
<th>Change in Length of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.050</td>
<td>2.070</td>
<td>2.090</td>
<td>2.000</td>
<td>2.040</td>
<td>-0.050</td>
</tr>
<tr>
<td>4</td>
<td>1.130</td>
<td>1.128</td>
<td>1.128</td>
<td>1.090</td>
<td>1.087</td>
<td>-0.050</td>
</tr>
<tr>
<td>6</td>
<td>1.043</td>
<td>1.043</td>
<td></td>
<td>1.033</td>
<td>1.031</td>
<td>-0.010</td>
</tr>
<tr>
<td>7</td>
<td>1.003</td>
<td>1.003</td>
<td>1.010</td>
<td>0.949</td>
<td>0.960</td>
<td>-0.050</td>
</tr>
<tr>
<td>8</td>
<td>1.361</td>
<td>1.348</td>
<td></td>
<td>1.342</td>
<td>1.329</td>
<td>-0.013</td>
</tr>
<tr>
<td>9</td>
<td>1.351</td>
<td>1.359</td>
<td>1.349</td>
<td>1.350</td>
<td>1.355</td>
<td>+0.012</td>
</tr>
<tr>
<td>10</td>
<td>1.205</td>
<td>1.230</td>
<td>1.210</td>
<td>1.239</td>
<td>1.220</td>
<td>+0.017</td>
</tr>
<tr>
<td>12</td>
<td>2.258</td>
<td>2.179</td>
<td>2.177</td>
<td>2.131</td>
<td>-0.048</td>
<td>-0.020</td>
</tr>
<tr>
<td>13</td>
<td>2.412</td>
<td>2.459</td>
<td>2.410</td>
<td>2.409</td>
<td>2.390</td>
<td>-0.019</td>
</tr>
</tbody>
</table>

**3-1**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Drill Rod</th>
<th>Sample Tube</th>
<th>Recording Chart</th>
<th>Length of Drive</th>
<th>Length of Sample</th>
<th>Change in Length of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.439</td>
<td>2.443</td>
<td>---</td>
<td>2.384</td>
<td>---</td>
<td>0.059</td>
</tr>
<tr>
<td>3</td>
<td>2.243</td>
<td>2.250</td>
<td>2.240*</td>
<td>2.175</td>
<td>---</td>
<td>0.058</td>
</tr>
<tr>
<td>4</td>
<td>2.500</td>
<td>2.500</td>
<td></td>
<td>2.187</td>
<td>---</td>
<td>0.303</td>
</tr>
<tr>
<td>5</td>
<td>1.922</td>
<td>1.920</td>
<td>1.910</td>
<td>1.851</td>
<td>1.840</td>
<td>0.053</td>
</tr>
<tr>
<td>6</td>
<td>1.932</td>
<td>1.982</td>
<td>1.933</td>
<td>1.921</td>
<td>1.863</td>
<td>0.057</td>
</tr>
<tr>
<td>7</td>
<td>2.490</td>
<td>2.500</td>
<td>2.485</td>
<td>2.306</td>
<td>---</td>
<td>0.205</td>
</tr>
<tr>
<td>8</td>
<td>2.495</td>
<td>2.492</td>
<td>2.482</td>
<td>2.275</td>
<td>---</td>
<td>0.220</td>
</tr>
<tr>
<td>9</td>
<td>2.290</td>
<td>2.290</td>
<td>2.276</td>
<td>2.258</td>
<td>---</td>
<td>0.048</td>
</tr>
<tr>
<td>10</td>
<td>2.368</td>
<td>2.350</td>
<td>2.348</td>
<td>2.218</td>
<td>---</td>
<td>0.042</td>
</tr>
<tr>
<td>11</td>
<td>2.500</td>
<td>2.500</td>
<td>2.486</td>
<td>2.445</td>
<td>---</td>
<td>0.045</td>
</tr>
<tr>
<td>12</td>
<td>2.500</td>
<td>2.497</td>
<td>2.486</td>
<td>2.384</td>
<td>---</td>
<td>0.045</td>
</tr>
<tr>
<td>13</td>
<td>2.064</td>
<td>2.064</td>
<td>2.055</td>
<td>2.001</td>
<td>---</td>
<td>0.063</td>
</tr>
<tr>
<td>14</td>
<td>2.460</td>
<td>2.463</td>
<td>2.446</td>
<td>2.415</td>
<td>---</td>
<td>0.045</td>
</tr>
<tr>
<td>15</td>
<td>2.497</td>
<td>2.497</td>
<td>2.484</td>
<td>2.445</td>
<td>---</td>
<td>0.045</td>
</tr>
<tr>
<td>16</td>
<td>---</td>
<td>2.500</td>
<td>2.490*</td>
<td>2.430</td>
<td>---</td>
<td>0.070</td>
</tr>
<tr>
<td>17</td>
<td>2.458</td>
<td>2.460</td>
<td></td>
<td>2.435</td>
<td>---</td>
<td>0.025</td>
</tr>
<tr>
<td>18</td>
<td>2.500</td>
<td>2.500</td>
<td></td>
<td>2.405</td>
<td>---</td>
<td>0.095</td>
</tr>
</tbody>
</table>

*Disk stuck.

**Note:** Methods used to obtain the above measurements were as follows:

1. Length of drive determined by direct measurement of the change in elevation of a reference mark on drill rod.
2. Length of drive determined by taking the difference in length from the shoulder of the sampler to the face of the piston before and after the drive.
3. Length of drive as recorded on the recording chart.
4. Length of sample determined by taking the difference in length of sample tube and the length from the sample tube shoulder to the top of the sample.
5. Length of sample determined by taking difference in length of drive and settlement recorded on the recording chart.
6. Change in sample length determined by direct measurement of the change in elevation of a reference mark on the settlement rod.
7. Change in sample length determined by taking the difference in length of drive and length of sample as measured on the sample tube (col 2-col 4).
8. Change in sample length recorded on recording chart.
Table C-2

RESULTS OF EVALUATION TESTS OF THE CUP-AUGER METHOD OF DENSITY DETERMINATION

<table>
<thead>
<tr>
<th>Increment No.</th>
<th>( \gamma_d ) As Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No. 1</td>
<td>Test No. 2</td>
</tr>
<tr>
<td>1</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>98.0</td>
</tr>
<tr>
<td>3</td>
<td>99.1</td>
</tr>
<tr>
<td>4</td>
<td>98.3</td>
</tr>
<tr>
<td>5</td>
<td>99.6</td>
</tr>
<tr>
<td>6</td>
<td>98.0</td>
</tr>
<tr>
<td>7</td>
<td>99.7</td>
</tr>
<tr>
<td>8</td>
<td>98.7</td>
</tr>
<tr>
<td>9</td>
<td>99.8</td>
</tr>
<tr>
<td>10</td>
<td>100.0</td>
</tr>
<tr>
<td>11</td>
<td>101.1</td>
</tr>
<tr>
<td>12</td>
<td>100.4</td>
</tr>
<tr>
<td>13</td>
<td>105.7</td>
</tr>
<tr>
<td>Average</td>
<td>99.9</td>
</tr>
<tr>
<td>Average Dry Density as Placed</td>
<td>100.3</td>
</tr>
<tr>
<td>Average Change in Dry Density</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

Notes: All densities in lb per cu ft. Test procedures used are described in paragraph 14, Appendix B. All tests were performed on medium sand MR-1. Tests 1 and 4 were compacted to obtain high density.

Average density change (dense specimens) = -0.95 lb per cu ft. Tests 2 and 3 were not compacted.

Average density change (loose specimens) = +0.65 lb per cu ft. Standard deviation of incremental densities about the average determined density = ± 2.3 lb per cu ft.
### Table C-3

RESULTS OF EVALUATION TESTS OF STANDARD DENSITY DETERMINATION PROCEDURE

<table>
<thead>
<tr>
<th>Increment No.</th>
<th>(\gamma_{di})</th>
<th>(\gamma_{df})</th>
<th>(\Delta\gamma_d)</th>
<th>(\gamma_{di})</th>
<th>(\gamma_{df})</th>
<th>(\Delta\gamma_d)</th>
<th>(\gamma_{di})</th>
<th>(\gamma_{df})</th>
<th>(\Delta\gamma_d)</th>
<th>(\gamma_{di})</th>
<th>(\gamma_{df})</th>
<th>(\Delta\gamma_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101.75</td>
<td>102.76</td>
<td>+1.01</td>
<td>99.79</td>
<td>98.45</td>
<td>+0.66</td>
<td>107.56</td>
<td>106.78</td>
<td>-0.78</td>
<td>109.12</td>
<td>105.23</td>
<td>-3.80</td>
</tr>
<tr>
<td>2</td>
<td>109.12</td>
<td>102.37</td>
<td>-6.75</td>
<td>104.58</td>
<td>94.18</td>
<td>-10.40</td>
<td>101.75</td>
<td>101.61</td>
<td>-0.14</td>
<td>92.96</td>
<td>94.91</td>
<td>+1.95</td>
</tr>
<tr>
<td>3</td>
<td>97.79</td>
<td>99.59</td>
<td>+1.80</td>
<td>92.96</td>
<td>95.23</td>
<td>+2.27</td>
<td>100.39</td>
<td>101.81</td>
<td>+1.42</td>
<td>96.53</td>
<td>95.74</td>
<td>-0.79</td>
</tr>
<tr>
<td>4</td>
<td>97.78</td>
<td>98.21</td>
<td>+0.46</td>
<td>92.96</td>
<td>92.53</td>
<td>-0.43</td>
<td>101.75</td>
<td>102.19</td>
<td>+0.44</td>
<td>99.07</td>
<td>93.40</td>
<td>-5.67</td>
</tr>
<tr>
<td>5</td>
<td>96.53</td>
<td>97.94</td>
<td>+1.41</td>
<td>86.55</td>
<td>86.07</td>
<td>-0.48</td>
<td>101.75</td>
<td>102.00</td>
<td>+0.25</td>
<td>92.95</td>
<td>94.37</td>
<td>+1.42</td>
</tr>
<tr>
<td>6</td>
<td>92.96</td>
<td>95.58</td>
<td>+2.62</td>
<td>80.10</td>
<td>82.15</td>
<td>+2.05</td>
<td>100.39</td>
<td>101.72</td>
<td>+1.33</td>
<td>94.12</td>
<td>95.05</td>
<td>+0.93</td>
</tr>
<tr>
<td>7</td>
<td>92.96</td>
<td>94.24</td>
<td>+1.28</td>
<td>73.10</td>
<td>73.15</td>
<td>0.05</td>
<td>103.14</td>
<td>102.28</td>
<td>-0.76</td>
<td>96.53</td>
<td>95.34</td>
<td>-1.19</td>
</tr>
<tr>
<td>8</td>
<td>92.96</td>
<td>91.93</td>
<td>-1.03</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>103.14</td>
<td>105.00</td>
<td>+1.86</td>
<td>92.95</td>
<td>93.83</td>
<td>+0.88</td>
</tr>
<tr>
<td>Average</td>
<td>97.73</td>
<td>97.83</td>
<td>+0.10</td>
<td>90.01</td>
<td>88.82</td>
<td>-1.19</td>
<td>102.48</td>
<td>102.92</td>
<td>+0.44</td>
<td>96.78</td>
<td>95.98</td>
<td>-0.80</td>
</tr>
</tbody>
</table>

**Notes:**
- All densities in lb per cu ft.
- Tests conducted by procedure outlined in paragraph 15, Appendix B.
- Average value of average density change = -0.36 lb per cu ft.
- Standard deviation of incremental density change = ± 2.1 lb per cu ft.
- Tests 1 and 2 - fine sand MR-2.
- Tests 3 and 4 - medium sand MR-1.
### Table C-4

**SUMMARY OF WEIGHT AND LENGTH MEASUREMENTS OF TWO SELECTED SAMPLE INCREMENTS BY FIVE DIFFERENT TECHNICIANS**

<table>
<thead>
<tr>
<th>Test</th>
<th>Technician</th>
<th>Length (cm)</th>
<th>Weight (g)</th>
<th>Density (Lb/Cu Ft, $D_s=7.620$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>1</td>
<td>7.478</td>
<td>595.2</td>
<td>109.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.490</td>
<td>595.2</td>
<td>108.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.500</td>
<td>595.3</td>
<td>108.7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7.475</td>
<td>595.2</td>
<td>109.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>7.465</td>
<td>595.4</td>
<td>109.2</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>7.482</td>
<td>595.3</td>
<td>108.9</td>
</tr>
<tr>
<td>2**</td>
<td>1</td>
<td>7.373</td>
<td>575.6</td>
<td>106.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.378</td>
<td>575.6</td>
<td>106.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.370</td>
<td>575.0</td>
<td>106.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7.373</td>
<td>575.8</td>
<td>106.9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>7.370</td>
<td>575.8</td>
<td>107.0</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>7.373</td>
<td>575.6</td>
<td>106.9</td>
</tr>
</tbody>
</table>

* Max difference between values

** Max difference between values

- Weight, 0.2 g
- Length, 0.035 cm
- Density, 0.5 lb/cu ft

- Weight, 0.2 g
- Length, 0.008 cm
- Density, 0.2 lb/cu ft
TEST 2-1
P=615 LBS/SQ FT  R=0.35 FT/SEC
RD=63.4%

TEST 2-4
P=570 LBS/SQ FT  R=0.47 FT/SEC
RD=106.3%

TEST 2-2
P=490 LBS/SQ FT  R=0.22 FT/SEC
RD=36.9%

TEST 2-5
P=490 LBS/SQ FT  R=0.45 FT/SEC
RD=39.1%

DO=2.875"  C=0.50%
NOTE: LINE OF ZERO VOLUME CHANGE
SETTLEMENT ROD JAMMED IN LAST PART OF TEST 2-11.

SETTLEMENT-LENGTH OF DRIVE RELATION
MEDIUM SAND
D₅₀=5.010” C=0.50%
SPECIFIC RECOVERY RATIO $\Delta L/\Delta H$

**TEST 3-1**
P = 600 LBS/SQ FT
R = 0.093 FT/SEC
RD = 95.7%

**TEST 3-2**
P = 600 LBS/SQ FT
R = 0.093 FT/SEC
RD = 94.8%

**LEGEND**
---
LINE OF ZERO VOLUME CHANGE

**SETTLEMENT - LENGTH OF DRIVE RELATION**

MEDIUM SAND

$D_s = 2.875$  $C = 0.50\%$
SPECIFIC RECOVERY RATIO ΔL/BH

TEST 3 - 5
RD = 98.7%

TEST 3 - 6
RD = 101.6%

TEST 3 - 7
RD = 49.1%

TEST 3 - 8
RD = 47.5%

NOTE: P = 2500 LBS/SQ FT
R = 0.0925 FT/SEC
--- LINE OF ZERO VOLUME CHANGE

SETTLEMENT-LENGTH OF DRIVE RELATION
FINE SAND
Ds = 3.000”  C = 1.0%
TEST 3-9
RD = 98.2%

TEST 3-10
RD = 100.0%

TEST 3-12
RD = 48.5%

NOTE: P = 2500 H/SQ FT
R = 0.0925 FT/SEC
--- LINE OF ZERO VOLUME CHANGE

SETTLEMENT - LENGTH OF DRIVE RELATION
FINE SAND
Ds = 3.000" C = 0.50%
NOTE:
P = 2500 LBS/SQ FT
R = 0.0925 FT/SEC
--- LINE OF ZERO VOLUME CHANGE

DENSE SAMPLES

SETTLEMENT - LENGTH OF DRIVE RELATION
FINE SAND
Ds = 3000"  C = 0.25%
NOTE: BOTTOM OF SAMPLES 1-1-1-4 FROZEN BEFORE REMOVAL FROM TANK.
SAMPLES 1-5-1-8 EXCAVATED FROM TANK.
NO MOLD DENSITIES DETERMINED.


**PLATE C-8**

**LOOSE SAMPLES**

**TEST 2-1**
- Density: 615 lbs/sq ft
- Rate: 0.35 ft/sec
- Mold density: 65.4%
- Sand depth: 3 ft

**TEST 2-2**
- Density: 490 lbs/sq ft
- Rate: 0.22 ft/sec
- Mold density: 36.9%
- Sand depth: 3 ft

**TEST 2-4**
- Density: 570 lbs/sq ft
- Rate: 0.47 ft/sec
- Mold density: 106.3%
- Sand depth: 3 ft

**TEST 2-9**
- Density: 570 lbs/sq ft
- Rate: 0.47 ft/sec
- Mold density: 102.0%
- Sand depth: 3 ft

**DENSE SAMPLES**

**TEST 2-4**
- Density: 570 lbs/sq ft
- Rate: 0.47 ft/sec
- Mold density: 106.3%
- Sand depth: 3 ft

**TEST 2-5**
- Density: 490 lbs/sq ft
- Rate: 0.45 ft/sec
- Mold density: 39.1%
- Sand depth: 3 ft

**Legend**
- O Incremental densities from sample tube
- △ Mold density samples

**Density-Depth Relation**

*Medium Sand*
- $d_s = 2.875$
- $c = 0.50\%$
TEST 2-10
P = 570 LBS/SQ FT RD = 96.6%
R = 0.27 FT/SEC S = 0.048 FT

TEST 3-1
P = 600 LBS/SQ FT RD = 95.7%
R = 0.093 FT/SEC S = 0.059 FT

TEST 3-3
P = 600 LBS/SQ FT RD = 36.1%
R = 0.093 FT/SEC S = 0.313 FT

TEST 3-4
P = 600 LBS/SQ FT RD = 30.2%
R = 0.093 FT/SEC S = 0.336 FT

LEGEND
○ ○ INCREMENTAL DENSITIES FROM SAMPLE TUBE
△ MOLD DENSITY SAMPLES
○ ○ 0.00 TRANSVERSE SETTLEMENT-CM.
DENSITY - DEPTH RELATION
FINE SAND

Ds = 3.000° C = 1.00 %

LEGEND
  O-O INCREMENTAL DENSITIES FROM SAMPLE TUBE
  ▲-▲ MOL DENSITY SAMPLES
  O-O TRANSVERSE SETTLEMENT -CM.

NOTE: P = 2500 LBS/SQ FT
      R = 0.0925 FT/SEC.
DENSITY - DEPTH RELATION
FINE SAND
D_s = 3.000"  C = 0.50%

NOTE: R=0.0925 FT/SEC
P=2500 LBS/SQ FT.
PLATE C-13

DENSITY-DEPTH RELATION
FINE SAND

Ds = 3.000"  C = 0.25%

NOTE:  P = 2500.0  LBS/SQ. FT.
R = 0.0925  FT/SEC.

LEGEND
- - INCREMENTAL DENSITIES
FROM SAMPLE TUBE
△△ MOLD DENSITY SAMPLES

S = 0.063 FT  RD = 96.6%
TEST 3-13

S = 0.048 FT  RD = 96.2%
TEST 3-14

S = 0.045 FT  RD = 45.4%
TEST 3-15

S = 0.070 FT  RD = 41.1%
TEST 3-16

TOP OF SAND
AVERAGE PLACED DENSITY

DENSE SAMPLES

LOOSE SAMPLES

TRANSVERSE SETTLEMENT
NOT MEASURED

DEPTH - FT
DENSITY - LBS/CU FT
ASSOCIATED REPORTS

<table>
<thead>
<tr>
<th>Study</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study of Materials in Suspension, Mississippi River</td>
<td>Feb 1939</td>
</tr>
<tr>
<td>Study of Materials in Transport, Passes of the Mississippi River</td>
<td>Sept 1939</td>
</tr>
<tr>
<td>Geological Investigation of the Alluvial Valley of the Lower Mississippi River</td>
<td>Dec 1944</td>
</tr>
<tr>
<td>A Laboratory Study of the Meandering of Alluvial Rivers</td>
<td>May 1945</td>
</tr>
<tr>
<td>Fine-Grained Alluvial Deposits and Their Effects on Mississippi River Activity</td>
<td>July 1947</td>
</tr>
<tr>
<td>Geological Investigation of Mississippi River Activity, Memphis, Tenn., to Mouth of Arkansas River</td>
<td>June 1949</td>
</tr>
<tr>
<td>Bank Caving Investigations, Morville Revetment, Mississippi River</td>
<td>Sept 1950</td>
</tr>
<tr>
<td>Investigation of Free Nigger Point Crevasse, Mississippi River</td>
<td>Dec 1950</td>
</tr>
<tr>
<td>Investigation of Mass Placement of Sand Asphalt for Underwater Protection of River Banks</td>
<td>Aug 1951</td>
</tr>
</tbody>
</table>