SUBSIDENCE OF GRANULAR MEDIA
AS A RESULT OF FLOODING

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1962

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
May, 1981

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PREFACE

This study is concerned with the analysis of subsidence of granular media when subjected to flooding. The primary objective is to determine the magnitude of subsidence for various granular materials. A secondary objective of the study is to correlate the subsidence of these materials to their physical properties. An exponential model is used in the analysis to determine relationships between relative density and subsidence. Relationships between coefficient of uniformity and subsidence and median particle diameter and subsidence are also investigated.

The author wishes to express his profound appreciation to his major adviser, Dr. T. Allan Haliburton, for his interest, assistance, and guidance throughout this study. Appreciation is also expressed to the other committee members, Dr. J. Vernon Parcher and Dr. Donald R. Snethen, for their assistance and interest. A note of thanks is given to Miss Duane Gupton and Mrs. Fran Andrews for their assistance in typing rough drafts of the manuscript, and to Ms. Charlene Fries for the outstanding preparation of the final copy and her editorial assistance. In addition, appreciation is extended to the U.S. Army Corps of Engineers and Hussey, Gay & Bell, Inc., without whose assistance this study could not have been completed.

Special appreciation is expressed to my wife, Miriam, and our daughters, Karen, Katherine, and Laura, for their sacrifices, patience, and moral support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a	regression coefficient (dimensionless)
b	regression coefficient (dimensionless)
C_u	coefficient of uniformity (dimensionless)
d_{50}	median particle diameter (mm)
D	diameter of circumscribing circle (in.) (see Figure 1)
D_i	diameter of inscribed circle (in.) (see Figure 1)
D_R	relative density (percent)
e	base of natural logarithms (dimensionless), and void ratio (dimensionless) (see Figures 3 through 7)
e_{max}	maximum void ratio (dimensionless)
e_{min}	minimum void ratio (dimensionless)
e_m	void ratio in moist state (dimensionless)
e_s	void ratio after subsidence (dimensionless)
G_s	specific gravity of solids (dimensionless)
N	number of particles
n_c	number of particle corners
p	percent by weight of material retained on a sieve
P	consolidation pressure (tons per square foot) (see Figures 3 through 7)
q	flow time (seconds)
R	particle roundness (dimensionless)
R_c	radius of circumscribing circle (in.) (see Figure 1)
R_i	radius of inscribed circle (in.) (see Figure 1)

$s\%$	subsidence (percent)
S_p	sphericity (dimensionless)
x	independent variable in regression analysis (dimensionless)
y	dependent variable in regression analysis (dimensionless)

CHAPTER I

INTRODUCTION

1.1 Subsidence of Granular Materials

1.1.1 Historical Background

The historical record of accomplishments in the field of construction is well documented. As early as the Fourth Dynasty of Egyptian rulers, ancient engineers recognized the problems associated with building on granular foundation materials. This has been demonstrated by the monuments and temples that were constructed on rock foundations and remain largely intact to the present time. On the other hand, those few structures that were built on the flood plain of the Nile River on alluvial deposits exist today in the form of scattered pieces of masonry located at various depths below the ground surface.

In biblical times, the problems associated with building on sand were commonly recognized. The Gospel, according to Saint Mark, contains a parable relating the permanence of structures built on rock foundations as opposed to the transient nautre of structures built on foundations of sand. In this same period of history, Vetruvius, engineer to Caesar, recognized and recorded suggestions for locations of encampments and cities with specific reference to the avoidance of alluvial deposits.

1.1.2 Contemporary Knowledge

The general knowledge that has been passed down through the centuries from ancient times has expanded in its scope and detail tremendously. Most of the detailed and specific knowledge of the behavior of granular media has been developed in the twentieth century. Extensive records of research exist on many topics concerning the behavior of sands under varied conditions of loading and excitation. Methods have been developed to determine with reasonable degrees of accuracy the effects of vibrations on the stability of sands. As a result of devastating earthquakes in Alaska, Japan, and Venezuela, a considerable amount of research has been accomplished concerning the liquefaction potential of sands. Terzaghi and Peck (21) have reported the consolidation or settlement characteristics of sand under static loading. Terzaghi (22) identified the principle of effective stress and the potential for consolidation of sands as a result of lowering groundwater elevations. Subsidence of ground surfaces as a result of hydraulic removal of sand particles, or piping, has been well documented.

In the existing body of contemporary knowledge concerning the behavior of sands, the research effort concerning subsidence of sands upon submergence has received little attention in comparison to the areas described above.

1.2 Purpose of Study

1.2.1 Evaluation of Subsidence Potential

The primary purpose of this study is to investigate and define the potential for subsidence of a select group of granular materials upon submersion. This topic was developed as a result of the author's knowledge of certain phenomena that have occurred for which the general mechanism of subsidence was known, but a method of quantification of subsidence was not available. Examples of these phenomena include the settlement of the Cathedral of St. John the Baptist in Savannah, Georgia, which has been in progress for a period of over eighty years and is attributed to the consolidation of foundation sands. Other examples are subsidence of structural floor slabs supported by sand fills, subsidence of entire structures on sand after recorded increases in groundwater elevation, and the subsidence of sands that have been used as backfill for bulkheads and utility systems.

1.2.2 Evaluation of Construction Materials

The secondary purpose of the study is to identify construction materials composed of sands and other granular media which have the greatest or the least potential for subsidence upon flooding. This is of particular importance in areas such as coastal plains, which have a preponderance of granular materails and a deficit of fine grained or plastic materials for use in construction. In this respect, the study area selected is located in the coastal plains of Georgia and South Carolina.

1.3 Objectives

1.3.1 Quantification of Subsidence Potential

It is the intent of this research to quantify subsidence potential for various granular materials. As such, the mechanism of subsidence has been relegated to secondary importance. The need for the quantification of subsidence potential in granular materials is evident in the construction industry literature that is in use at present. For example, sales publications by a major manufacturer of utility piping in the United States recommends placement of sand trench backfill material with compaction by wetting or flooding. This literature, however, does not prepresent requirements for quantity of water to be added nor does it state the degree of consolidation that may be obtained by this method. Numerous other examples of similar recommendations exist in published literature without reference to material property, quantity of water required, method of accomplishment or anticipated results.

1.3.2 Correlation of Subsidence and Material Properties

A secondary objective of this study is to correlate the magnitude of subsidence upon flooding to physical properties of materials which include gradation, particle shape and density of the granular mass. These correlations are intended to be an aid to the construction industry and the engineering profession in the prediction of subsidence under conditions of flooding for the use of various types of sands and granular construction materials. Since methods exist for estimating the relative density of sands in the field, the establishment of a relationship between density and subsidence potential will add accuracy to the prediction of deformations.

In consideration of the objective to attempt correlation of material properties to subsidence potential, only materials that are in present use in construction were selected for testing in this study. These materials are described in detail in the following chapters.

1.3.3 Identification of Needed Research

The need for research in the area of flooding-induced subsidence is evident. The final objective of this study is therefore to identify potential areas in which research efforts in this field may be directed. Specific recommendations for further research are contained in the final chapter of this study.

CHAPTER II

LITERATURE REVIEW

2.1 Properties of Granular Media

2.1.1 Physical Properties

Physical and mathematical modeling of fabric of soils has been accomplished by many researchers. Most of these efforts relied upon the use of spherical particles as a method for defining particle shape and packing array configurations. Muskat (19) identified two cases of packing for spherical particles. The first case consisted of a cubic array of particles which is definitive of the maximum porosity or void ratio of the mass. The second case identified the rhombohedral condition of packing which is descriptive of the minimum void ratio or porosity of the mass. In addition to these two regular or uniform packing arrays, Muskat reported that at the angularity of natural sand grains tends to produce bridging which results in a random packing and therefore generally higher void ratios in the natural state than those obtained by the testing of spherical particles. Mitchell (18) has presented extensive data concerning soil fabric and structure. Of particular interest in this study were his descriptions of particle assemblages for granular matrix situations in sands. Mitchell further reported that a given cohesionless soil could have many different fabrics or particle arrangement systems and at the same time have a constant void ratio or relative density. In addition to the two cases of packing or spherical particles as reported by Muskat, Mitchell identified three other cases. These cases of ideal packing represent conditions between those corresponding to the maximum and minimum ratios of the mass.

Burmister (2) reported on the grading-density relationships of sand in 1938. He determined that the grading-density relationships of granular materials could be used to proportion sands artifically to provide maximum density upon compaction. In further research, Burmister (3) described the importance of relative density as a definitive aid in soil mechanics. His discussion of relative density relationships on soil behavior included relations between penetration resistance and relative density, angle of friction and relative density, settlement and relative density and the effect of variations in relative density on permeability. Hutchinson and Townsend (9) determined that gradation of sand explained partially the variation in minimum densities obtained for a particular compaction technique. They further identified the need for a minimum density test which reflects changes due to grading.

Particle shape generally has two categories of classification. The first, as described by Wadell (23), concerns roundness or angularity of particles. Wadell defined angularity as the ratio of the average radius of the corners of a particle to the radius of the maximum circle that could be inscribed within a projected image of the particle shape. The second commonly used measure of particle shape is sphericity. Riley (20) has reported on the means developed by different researchers for calculating sphericity. Also, he has presented a method based on projection to describe sphericity in terms of the square root of the ratio of the diameter of a maximum sized circle that can be inscribed in a projected particle shape to the diameter of a circle which circumscribes the projected outline of the particle. Methods described by these two researchers are considered to be direct measurement methods. Indirect measurement methods have been developed which include measuring the flow time of sand passing through an orifice and the use of hydraulic conductivity of water through a soil mass.

Statistical definition of granular media has been accomplished by Field (7) and Fletcher (8). This research indicated that for particles placed randomly in a given space, there would be a relationship between the mean number of points in contact per particle and the density of the mass. He further indicated that this relationship would be linear. His explanation of experimental deviation from theoretical relationships included sample disturbance and errors due to segregation. He also reported that a third source of deviation was the effect of plane boundaries of testing equipment on performance of the granular media during experimentation. Fletcher, by developing Field's research into a statistical definition of a granular medium, established a basis for theoretical determination of vertical deflection patterns within an idealized mass composed of spherical particles. He equated these theoretical predictions to test results for a well rounded river gravel of uniform particle size and found the results for this material to be equally valid as those for spherical particles.

2.1.2 Characteristics of Behavior

Any study concerning the potential deformation of soils must also take into account the factors which retard deformation. Koerner (11), in his investigation into the effect of particle characteristics on soil strength, concluded that the strength of sands was materially affected by variations in certain physical properties of the material. He found that soils with more angular particles and lower sphericities had significantly higher angles of drained shearing resistance. He also concluded that the coefficient of uniformity had a negligible effect on drained shearing resistance in quartz soils but caused correspondingly higher drained shear angles for soils composed of feldspar and calcite. Lee, Seed, and Dunlop (16) investigated the effects of moisture on the strength of a clean sand. For the particular sand used in their experiments, it was found that the material was considerably stronger in the oven-dry condition than in the saturated state. The strength of air-dried sand was intermediate between these two extremes. The significance of the work by these gentlemen was the fact that over-dry and air-dry sand could be loaded to a condition of stability in triaxial compression but would fail immediately upon the addition of water. This was explained by microscopic examination of the material which revealed the presence of fine cracks with possible films of clay.

Consideration of consolidation of sands has been addressed by Wu (24). A fixed ring consolidometer was used with loading accomplished in the conventional manner. The tests performed by Wu were conducted on saturated samples of coarse grained soils and resulted in the conclusion that there was a marked decrease in compressibility with increasing particle size. Wu further concluded that the increase in relative density of the soils resulting from one-dimensional loading was of significance only for fine and medium sands and that coarse sands and gravels have sufficiently low compressibilities to prevent significant change in relative density upon loading. These results are qualified by the nature of loading and were not considered entirely valid for the condition of laterally unconfined soils with corresponding lateral displacement in addition to vertical deformation.

2.1.3 Hydraulic Properties

Testing involving the application of water to a soil must be accomplished in a manner to prevent excessive turbulent flow in pore spaces and to avoid a hydraulic gradient sufficiently high to dislodge individual particles from the specimen mass or create liquefaction of the soil. Means and Parcher (17) described a method of determining critical flow velocity which was used to establish rate of water application in this study. The relationship used is that of velocity with respect to hydraulic gradient in which the velocity associated with laminar flow is proportional to the first power of the hydraulic gradient.

2.2 Subsidence

2.2.1 General Documentation

In a commentary on collapsing soils, Dudley (6) postulated the conditions required for a soil to have a collapse potential. The major components of collapsing soils were reported to be those of bulky shape which occur in silts, sands, and gravels. Also, for collapse to occur the soil must have a natural structure that is characterized by a high void ratio and must have a temporary source of strength to hold the soil particles in position against shearing forces. The sources of strength are generally in the form of tension between soil particles caused by capillarity in the water between particle surfaces at contact points or the presence of silt grains forming buttresses between sand particles with the former being in a state of capillary-induced tension. A third factor reported by Dudley as the cause of temporary strength is the presence of a cementing agent such as iron oxide. Of these three causes, the opinion of Dudley is that capillary tension is the main factor in providing the temporary strength of collapsing soils. In all cases, the triggering action for collapse is attributed to the addition of water.

The Committee on Placement and Improvement of Soils of the Geotechnical Engineering Division of the American Society of Civil Engineers (4) has listed the qualitative methods of predicting susceptibility to collapse as proposed by several researchers. Of these methods, only that proposed by Jennings and Knight (10) was adaptable to granular materials as well as fine grained soils.

2.2.2 Subsidence of Sands

The method proposed by Jennings and Knight for predicting the subsidence of sands involved the performance of two consolidation tests. One test involved the consolidation of a specimen at natural moisture content to a predetermined pressure and then flooding the sample and observing the resulting deformation. The second consolidation test was performed on the same material, at the same condition of initial void ratio but with the specimen pre-wetted before loading. The hypothesis of Jennings and Knight was that the subsidence potential was the difference in void ratio between the two compression curves at a given load. This is not exactly valid in that the magnitude of deformation for the moist sand upon flooding was less than the difference between the variation of void ratio prior to flooding and the void ratio of the pre-wetted sample at the stress level at which collapse was initiated.

2.3 Testing

2.3.1 Testing for Physical Properties

The testing for the basic properties of samples used in this study was accomplished under the guidelines and criteria established by Lambe (15). The tests conducted under the procedures outlined by Lambe includthose for specific gravity, gradation and grain size characteristics, and moisture content. Testing to determine maximum and minimum void ratios for relative density computations were conducted in accordance with the procedures given by the American Society for Testing and Materials (1). Sphericity and roundness were determined by testing in accordance with procedures developed by Riley (20) and Wadell (23), respectively. The exception to this was the use of a test devised by Dickin (5) in which sphericity was measured on the basis of flow time of a material of given median particle diameter through an orifice. The empirical equation for this relationship is discussed in detail in the following chapter.

2.3.2 Testing for Subsidence

The test method for subsidence prediction by Jennings and Knight as described in section 2 of this chapter was modified for use in this study. Other test methods reviewed for possible use in the study involved testing of pre-wetted or saturated granular materials, vibratory testing for subsidence potential, and static testing to determine magnitude of consolidation as a time-rate process. As such, they were not considered applicable to the type of testing required by the objectives of this study.

2.3.3 Sample Preparation

Consistent methods of sample preparation are of particular importance in preparing sand specimens for testing. Repeatability of test results may vary widely for the same materials at the same density but with variations in the mass caused by nonuniform methods of preparation. Ladd (14) reported these variations in results of cyclic stability testing for sands. In this mode of testing, the discrepancies were especially noticeable for fine to coarse sands in a dense condition. Ladd also reported variations of results in liquefaction testing for sands. These variations were attributed to segregation and a resultant variation in the structure of the sand for repetitive tests with the same material.

CHAPTER III

IDENTIFICATION OF MATERIAL PROPERTIES IN SUBSIDENCE TESTING

3.1 Physical Properties

3.1.1 Specific Gravity and Gradation

Specific gravity testing was performed in accordance with procedures outlined by Lambe (15) and results were recorded to three decimal places. Presentation of the results, along with the results of all other physical property tests are presented in Chapter IV.

3.1.2 Sphericity and Roundness

For determination of particle sphericity, both direct and indirect methods of measurement were used. The direct method consisted of projection sphericity as described by Riley (20). In this method, microphotographs were made at 25 power magnification with black and white negative film. The developed film was mounted on 35 mm slide frames and projected onto paper which permitted the tracing of particle outlines. This allowed the direct measurement of inscribed and circumscribed circles as shown in Figure 1. The equation used to calculate the sphericity of an individual particle is

$$S_p = \sqrt{\frac{D_i}{D}} \qquad (1)$$

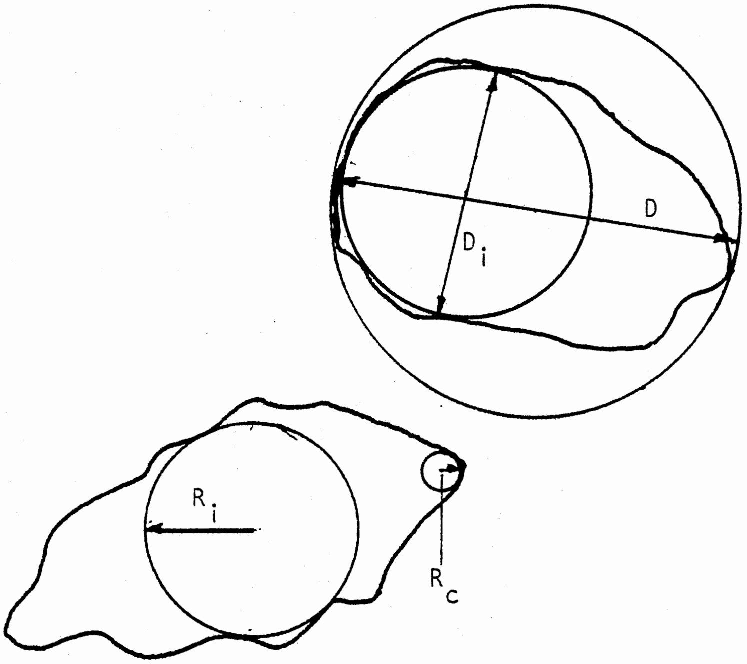

Figure 1. Particle Measurements for Determination of Sphericity and Roundness

where S_p is the sphericity of the particle, D_i is the diameter of the inscribed circle, and D is the diameter of the circumscribing circle. With this method, the calculation of average sphericity of particles within a mass is obtained by repeating the above process for at least 50 particles from the material retained on each of the sieves used to determine gradation. Average sphericity for a given sieve fraction is calculated by the formula

$$\text{Avg } S_p = \frac{S_p}{N} \tag{2}$$

where N is the number of particles examined. The average value for the mass is calculated from the relation

$$S_p = \Sigma(\text{Avg } S_p \times p) \tag{3}$$

where p is the percent by weight of particles retained on the applicable sieve fraction.

An indirect method of measurement as reported by Dickin (5) involves the use of flow measurement for the determination of sphericity. In this method, the time required in seconds for 500 grams of dry sand to flow through a one-quarter inch diameter opening is measured. This value is then used in the empirical equation

$$S_p = \frac{196\ d_{50} + 144 - q}{146\ d_{50} + 112} \tag{4}$$

where d_{50} is equal to the median grain diameter of the sand and q is the flow time in seconds. The advantages of this indirect method of measurement are in the reduced time it takes to determine sphericity and in the greatly increased mass of material that can be tested. However, by comparison with results of projection methods for this study, it was determined that the method is not accurate for materials having median particle diameters greater than 0.60 mm. As a result of this determination, projection methods were used on two of the five materials tested.

Roundness or angularity was determined by projection methods as described by Wadell (23) and by comparative examination with published photographs. In the projection method, the roundness was determined by

$$R = \frac{\Sigma r_c}{n_c R_i} \tag{5}$$

where r_c is equal to the radius of each corner of the particle, n_c is the number of corners, and R_i is the radius of the maximum circle that can be inscribed in the projected particle outline. The method of measurement for roundness is demonstrated in Figure 1.

3.2 Maximum and Minimum Void Ratio

3.2.1 Methods Investigated

The literature on this subject contains many diverse methods for obtaining maximum and minimum void ratios in granular materials. Concerning minimum void ratio, Youd (25) reported that maximum densities were best obtained by repeated straining in simple shear as opposed to the procedures outlined in ASTM D 2049. In contrast to this, Kolbuszewski (12) reported that maximum densities could best be obtained by compaction of sand in three layers in a Proctor mold placed under water with the compaction energy delivered by pneumatic or electric hammers.

For minimum density, or maximum void ratio, Kolbuszewski (13) recommended that the dry material be placed in a graduated cylinder and then rapidly inverted. In this method, measurement of minimum density was obtained by the known weight of the material and the observed volume in the cylinder after inversion. This method is one of several reported by Kobuszewski which provides densities lower than those obtained by the ASTM method. The lower densities result from entrapped pockets of air within the mass caused by placement of material at a rate faster than that of the dissipation rate of the air pressure. Youd reported that a minimum density or maximum void ratio was best obtained by pouring granular material through water. Densities obtained in this manner are lower than those obtained by pouring dry material through a funnel, if the pouring rate is in excess of the ability for water to dissipate through the media.

3.2.2 Determination of Values

In the determination of maximum and minimum void ratios, the major objective was to perform these tests in a manner which provided consistency from material to material. In this respect, the ASTM method 2049 was employed. Maximum void ratio was obtained by using a 0.1 cubic foot compaction mold. Minimum density was obtained on a vibrating table using a 0.5 cubic foot mold.

Maximum void ratios for the materials were determined to be consistent with those published for similar types of sand. However, maximum densities seemed to be slightly below those values obtained by other researchers. The reason for this is attributed to densification of material in the dry state as opposed to saturated material and a possible deficiency in the frequency range of the vibrating table.

3.3 Subsidence Testing

3.3.1 Apparatus

Subsidence testing was conducted in a Wykeham Farrance consolidation machine. The machine had a loading arm ratio of 11:1. Compensation for the 350 grams of water added at each submersion was accomplished by the use of a specially constructed weight platen of 31 grams. The dial used to measure deflections was graduated in 0.002 mm divisions. A fixed consolidation ring was used throughout the testing which had a height of 0.75 inches and a diameter of 2.5 inches.

3.3.2 Sample Preparation

All samples were placed in the consolidation ring at a moisture content near 5 percent. Sample placement was accomplished in three layers with densification obtained on each layer by prodding with a 1-inch diameter steel rod. When testing a series of three samples at a constant relative density, trial and error methods were employed to obtain consistent initial densities. The number of blows to densify each layer in the consolidation ring were recorded. The final or uppermost layer was densified to a height slightly over the top of the ring. The material was then struck off with a straight knife edge and remaining grains in the specimen that had been dislodged were replaced by pressure from a glass plate. The specimen was then weighed and the weight of the ring and bottom stone deducted to determine the density of the material. Relative density for the specimen was then calculated. If the relative density obtained was different from the standard relative density desired for the particular test, the process was repeated with a different number of blows for each layer of material. By recording the number of blows for each specimen and the corresponding relative density obtained, sample preparation was reduced to approximately three trials per test.

3.3.3 Test Procedure

Samples were tested at the preparation moisture content and loaded to the consolidation pressure at which subsidence was to be induced. At the subsidence consolidation pressure, water was added to the consolidometer by slowly pouring at the edge of the container. At the time water was added, the compensating weight platen was placed on the loading arm. Subsidence values were obtained at three consolidation pressures for each of three initial relative density conditions. Consolidation pressures for subsidence measurements were 0.25 TSF, 1.00 TSF, and 4.00 TSF. Upon completion of the subsidence cycle in the test, the specimen was unloaded to obtain rebound values to the 0.25 TSF pressure. This was done as a matter of interest in the elastic compression properties of the materials investigated. The results obtained from rebound observations are not used in this study.

Water used to induce subsidence was de-aired and de-mineralized. The addition of water was accomplished so that saturation of the sample occcurred from the bottom to the top. This was done to eliminate as much as possible the creation of air bubbles within the specimen. Water temperature was maintained between 65 and 70°F, as a matter of consistency. For the purpose of the tests conducted for these investigations, a wider range of water temperature would not have materially affected the results.

CHAPTER IV

MATERIAL PROPERTIES

4.1 Types and Sources

4.1.1 Dune Sand

Wind deposited dune sand from Hilton Head Island in South Carolina was obtained as one of the samples to be tested. This material is composed of fine particles of quartz with traces of shell fragments. Since this material comprises the majority of available earth materials on the island, it is used extensively in construction. Typical uses include compacted subgrades for streets and highways, controlled earth fills, containment dike fills, backfill for bulkheads, and backfill for utility trenches. The material has a history of construction-associated problems. Its sphericity combined with low moisture content has caused numerous types of subgrade and foundation failures in the absence of stabilization. The material is very uniform and fine, and has caused severe problems with storm and sanitary sewer subsidence by infiltrating into open pipe joints. For the purposes of this study this material has been assigned the code HHD.

4.1.2 Coarse Processed Sand

This material was obtained from Coastal Abrasives, Inc., in Hardeville, South Carolina. It is a coarse, uniform sand that is processed primarily for the purpose of use in filter media. The material is alluvial in origin and is obtained by dredging from the flood plain deposits along the Savannah River. In addition to its use as filter sand, the material has been used as bulkhead backfill to provide free drainage. It was selected primarily because of its median grain size. This material was assigned the code CAC.

4.1.3 Processed Aggregate Sand

Aggregate sand was also obtained from Coastal Abrasives, Inc., in Hardeville, South Carolina. This material is of the same origin and is recovered in the same manner as the Coastal Abrasives' coarse sand. It is primarily processed for use in concrete mixes, but has been used for other purposes such as road subgrades and high density foundation backfills. The selection of this material was based on its coefficient of uniformity. It has been assigned the code CAA for subsequent use.

4.1.4 Hydraulic Dredge Spoil

The hydraulic dredge spoil was obtained from the Georgia Ports Authority's Garden City Terminal. The Authority maintains a containment for dredged spoil for material taken from the bedload of the Savannah River during maintenance dredging operations. The material is composed of quartz particles. It was selected for testing on the basis of its coefficient of uniformity. This material is used extensively in all types of construction for the Georgia Ports Authority. This has included pavement subgrades, stabilized pavement bases, bulkhead backfill, compacted earth fills, surcharge fills, and dike construction. It has been used in approximately 60 percent of construction development in the past 10 years. The material code GPS has been assigned to this soil.

4.1.5 Rock Screenings

Screenings from crushed rock, graded to remove particles larger than the No. 8 sieve, have been used extensively in commercial, municipal, and industrial development in the Savannah, Georgia, area. These materials have been typically used in applications which require high density and maximum resistance to deformation under both static and transient load conditions. The material consists of a crushed metaquartzite with a slight content of mica. It originates from the processing operations of the Superior Stone Quarry in Augusta, Georgia. The basis of selection for this material was its very value for coefficient of uniformity. The code assigned to this material is GRS.

Table I is a summary of material code designations along with a brief description of each material.

4.2 Physical Properties

4.2.1 Specific Gravity

The specific gravity of the five materials tested varied from a low value of 2.641 for CAC to a high value of 2.688 for GRS. When rounded to two decimal places, the variation in specific gravity for these materials is not significant. The slight variation between the two materials from the same source, CAC and CAA, is explained by the difference in processing for these two materials.

4.2.2 Particle Size Distribution

The results of sieve analyses on the materials tested are presented in Table II. Graphic representations of particle size distribution are

TABLE I

MATERIAL DESIGNATIONS

Material Code	Description
HHD	Hilton Head Island, S. C. dune sand composed of fine particles of quartz with traces of shell fragments.
CAC	Coastal Abrasives coarse sand from Hardeeville, S. C. Processed to specified gradation for commercial purposes.
CAA	Coastal Abrasives aggregate sand, origin as for CAC. Processed for use in concrete mixes.
GPS	Georgia Ports Authority hydraulic dredge spoil. Material taken from bed load of Savannah River.
GRS	Graded rock screenings composed of crushed metaquartzite from Augusta, Ga.

TABLE II

PERCENTAGES BY WEIGHT OF MATERIALS PASSING THE SIEVE SERIES

Material Code	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
HHD	100	100	100	100	99.1	84.4	8.5	0.5
CAC	100	100	97.9	14.2	0.8	0.4	0	0
CAA	100	98.8	95.8	31.2	44.3	9.1	1.0	0.4
GPS	100	98.1	89.6	74.9	48.1	20.2	7.7	0.7
GRS	100	100	100	82.0	58.9	38.0	20.7	10.5

shown on Figure 2. Median grain size diameters varied from 0.22 mm to 1.53 mm. The finest material was HHD and the coarsest CAC with the remaining materials having median grain diameters between the two ranges given above. Coefficients of uniformity varied from 1.45 for CAC to 8.14 for GRS. The remainder of the materials had intermediate values between the two extremes. Three of the samples--HHD, CAC, and CAA--were of the poorly graded classification. GPS and GRS materials were of the well graded category.

4.2.3 Shape

The particle sphericity of all materials, with the exception of HHD, was in the range of 0.73 to 0.79. HHD had an average particle sphericity of 0.86. Angularity, as measured by direct observation, varied from 0.25 to 0.49. The most angular material was GRS. The CAC and CAA materials were found to be of the sub-angular category; the GPS material of the sub-rounded classification; and the HHD of the well rounded category.

4.2.4 Maximum and Minimum Void Ratio

The maximum void ratios determined for the five materials ranged from 0.778 for GPS to 1.034 for GRS. The magnitude of the latter value is attributed to the angularity of the material. Minimum void ratios varied from 0.503 for GRS to 0.639 for CAC.

The physical properties of all materials are presented in Table III.

TABLE III

MATERIAL PROPERTIES

Material Code	G_s	d_{501}mm	C_u	S_p	R	e_{max}	e_{mm}
HHD	2.680	0.22	1.60	0.86	0.49	0.868	0.575
CAC	2.641	1.53	1.45	0.74	0.30	0.891	0.639
CAA	2.645	0.64	2.53	0.76	0.30	0.846	0.635
GPS	2.658	0.57	3.80	0.79	0.41	0.778	0.525
GRS	2.688	0.43	8.14	0.73	0.25	1.034	0.503

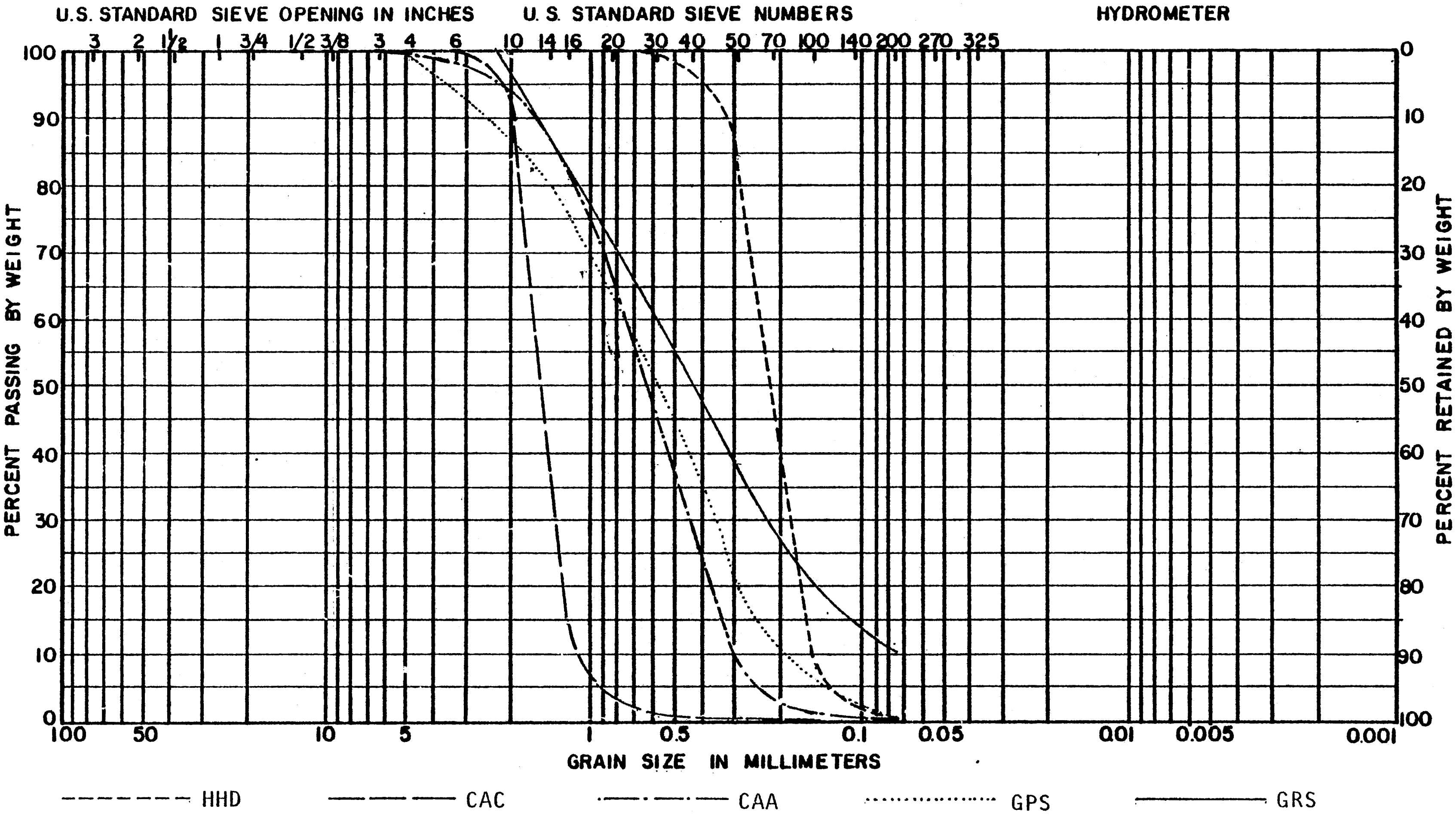

Figure 2. Sieve Analyses

CHAPTER V

RESULTS AND ANALYSIS

5.1 Results of Subsidence Testing

5.1.1 Test Series Configuration

The test series for the five materials used in this study was arranged to provide an array of three initial relative densities of 17 percent, 36 percent, and 62 percent with subsidence measurements made at consolidation pressures of 0.25 TSF, 1.00 TSF, and 4.00 TSF for each of the three initial conditions of density. This configuration required the performance of 45 consolidation and subsidence tests. Six of the 45 tests were not performed because it was determined in the initial series of tests for CAC that there was no subsidence at the four ton per square foot consolidation pressure at the initial relative density of 17 percent.

Tests were performed in sequence for each material progressing from the lowest initial relative density to the highest. Also, for each value of initial relative density, tests were performed in sequence from the lowest to the highest values of consolidation pressure. Upon the completion of individual consolidation tests, calculations were performed to determine the quantitative results prior to initiation of subsequent tests. This was performed to determine the need for continuing a given series.

5.2 Results

The basic parameter sought in the test series was the magnitude of subsidence upon flooding. This value was determined by the equation

$$s\% = \frac{e_m - e_s}{1 + e_m} \times 100 \tag{6}$$

where e_m is the void ratio of the moist material at the consolidation pressure of submersion, e_s is the void ratio of the material upon completion of subsidence, and s% is the subsidence expressed as a percentage of the thickness of the layer of material prior to submersion. This model was chosen to represent the magnitude of subsidence upon flooding since the product of the values derived from the equation and layer thickness gives a direct value of magnitude of subsidence for any thickness of a deposit of material. Figures 3 through 7 show consolidation and subsidence for each test in graphic form. The rebound curves shown on these figures were provided to demonstrate the degree of elasticity of each of the materials tested. The values, thus obtained, are not used in the analyses in this study because they would relate to field conditions only upon removal of overburden after subsidence caused by flooding.

A comparison of subsidence results to material designations indicates that the coarse uniform CAC material had the least subsidence. The well graded GRS material exhibited the most subsidence. The material that had the second highest subsidence upon submersion was the GPS sand. The results of all tests for all materials are given in Table IV.

The three initial relative densities for samples in the test series were used to provide a common point of beginning for consolidation of each material. Other than for that purpose, these values have little meaning because of the development of increasing relative densities resulting from increasing the pressure application. Relative densities corresponding to the state of the sample after consolidation to submersion

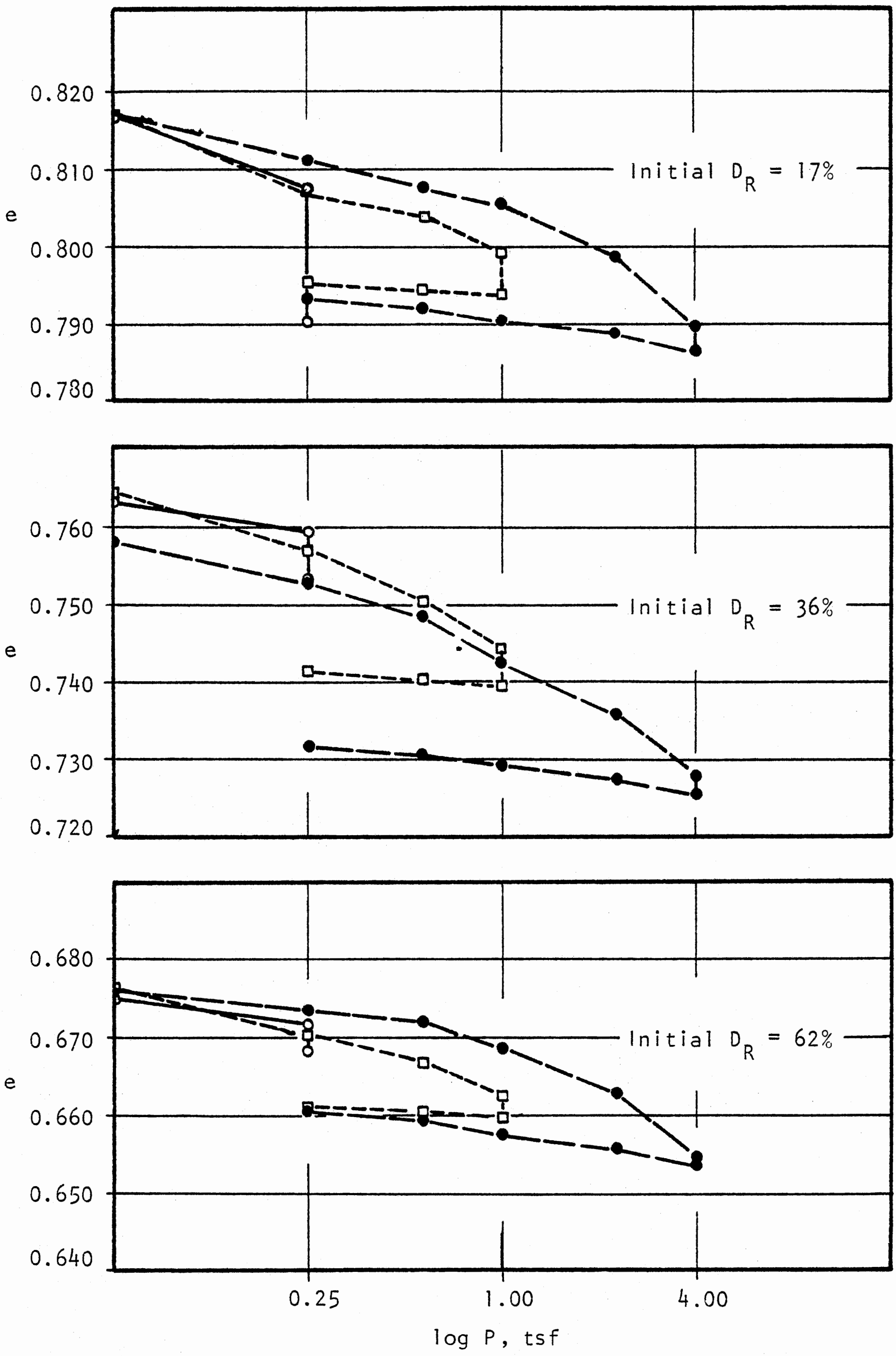

Figure 3. Consolidation and Subsidence, HHD

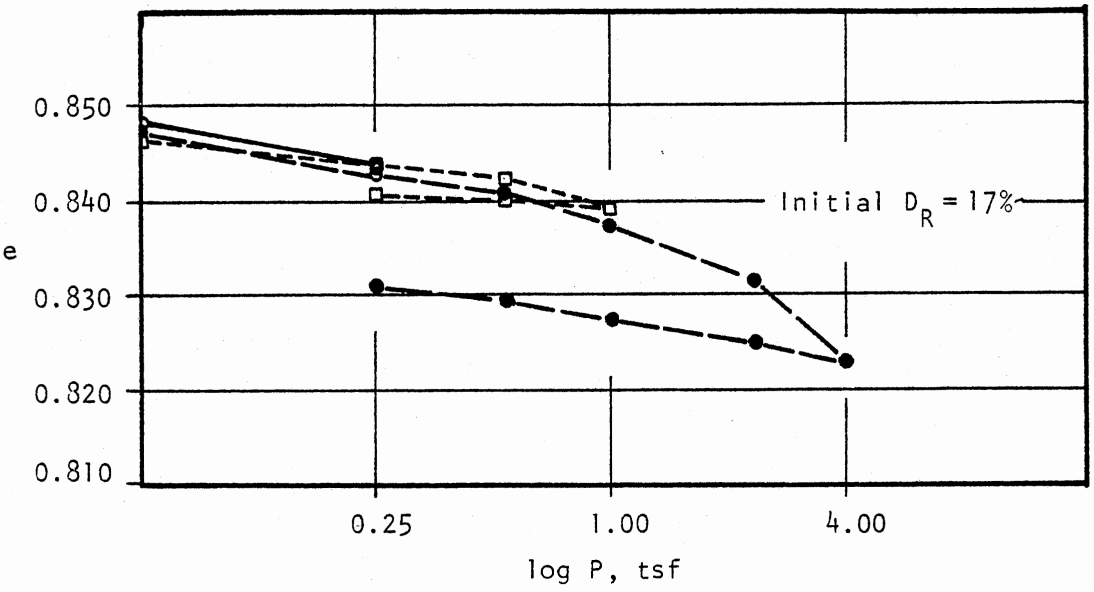

Figure 4. Consolidation and Subsidence, CAC

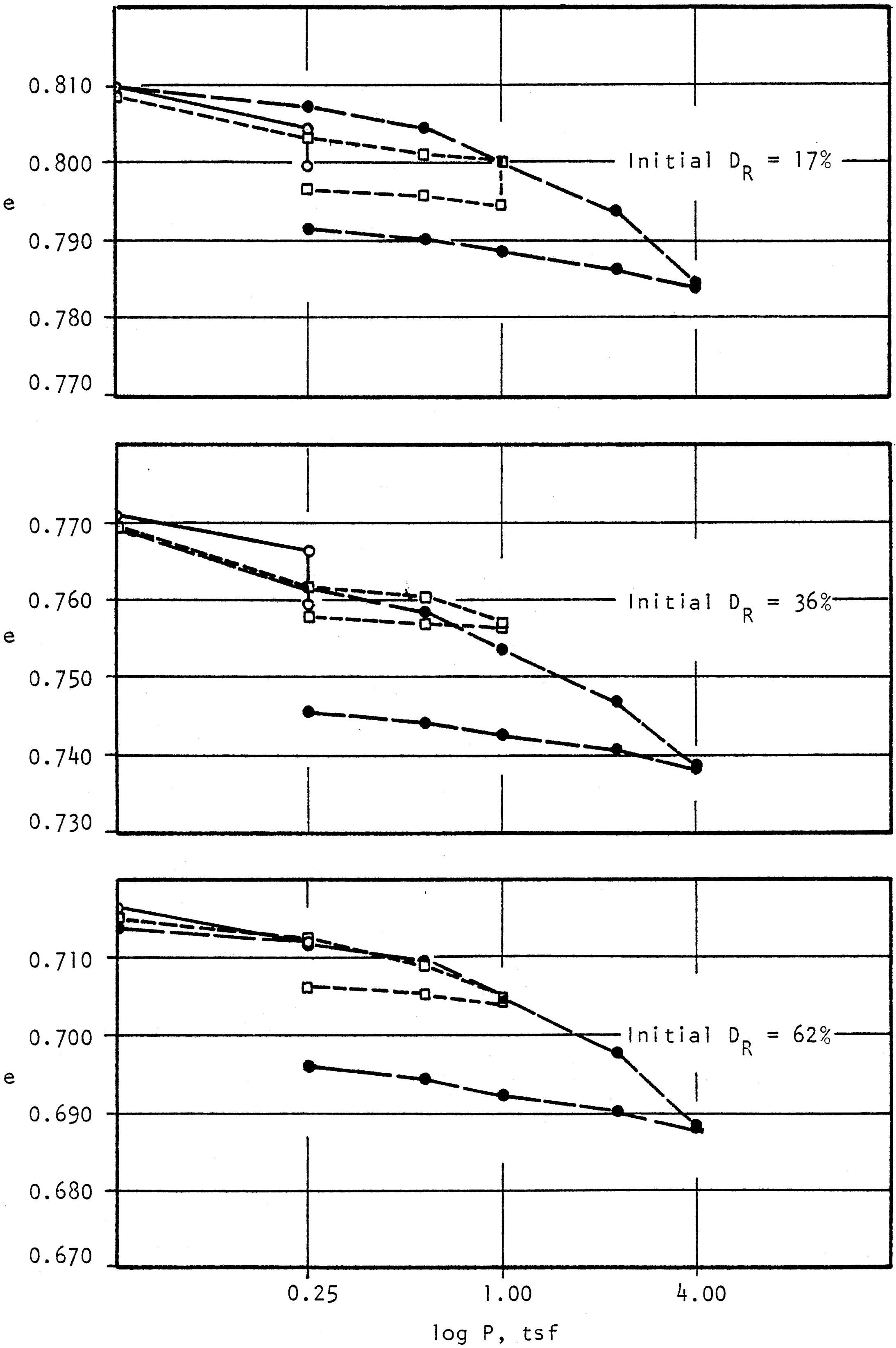

Figure 5. Consolidation and Subsidence, CAA

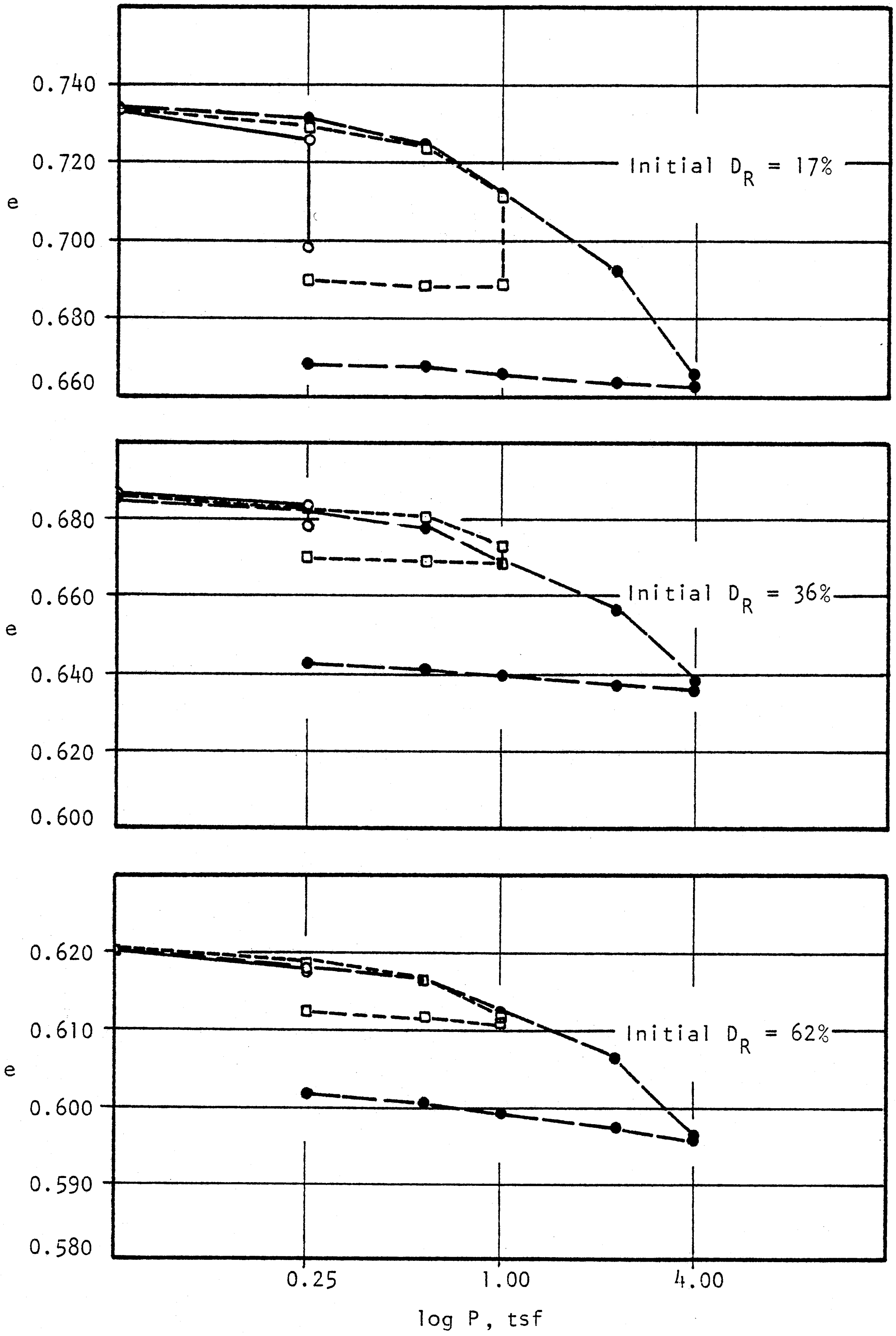

Figure 6. Consolidation and Subsidence, GPS

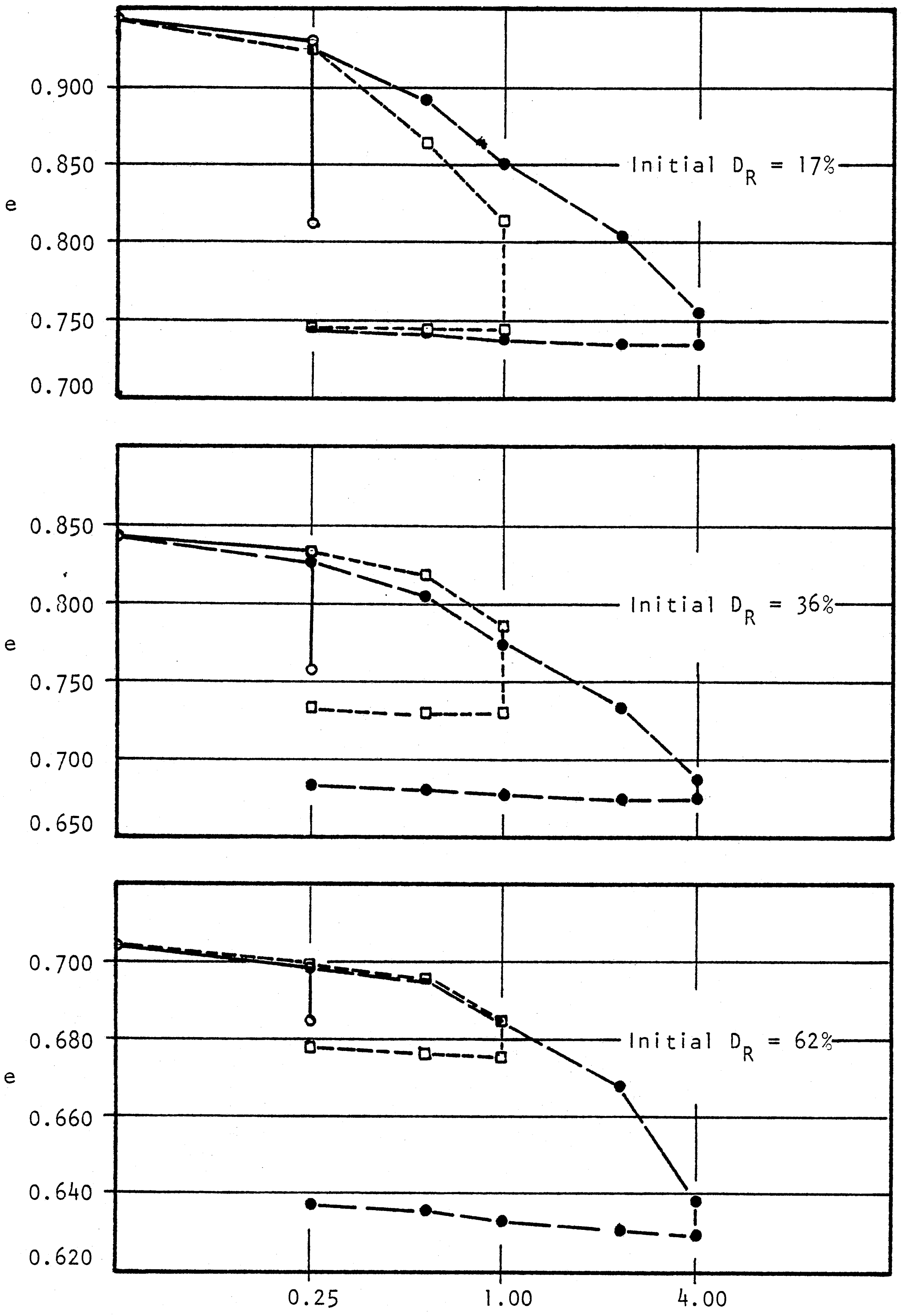

Figure 7. Consolidation and Subsidence, GRS

TABLE IV

PERCENTAGES OF SUBSIDENCE AT VARIOUS INITIAL RELATIVE DENSITIES AND CONSOLIDATION PRESSURES

Material Code	Initial D_R = 17%			Initial D_R = 36%			Initial D_R = 62%		
	0.25*	1.00	4.00	0.25	1.00	4.00	0.25	1.00	4.00
HHD	0.963	0.300	0.173	0.335	0.264	0.145	0.470	0.150	0.060
CAC	0.016	0.005	0	(Tests discontinued after 0% subsidence for CAC)					
CAA	0.261	0.294	0.022	0.419	0.040	0.012	0.047	0.018	0.012
GPS	1.559	1.333	0.192	0.303	0.293	0.189	0.025	0.050	0.063
GRS	6.139	3.857	1.156	4.192	3.217	0.853	0.813	0.564	0.531

*Consolidation Pressure in Tons per Square Foot pressure were calculated for each test. These values of relative density are presented in Table V in the same configuration as those values for subsidence that were presented in Table IV.

5.3 Analyses and Comparisons

5.3.1 Analysis of Test Results

It is interesting to note the variations in the slopes of compression curves in Figures 3 through 7. For example, in Figure 3, the three compression curves between the 0 and 0.25 consolidation pressures are highly variable with no apparent repeatability between the tests for the three conditions of initial density. This is attributed to variations in particle orientation from sample to sample and possibly to different degrees of segregation during preparation of samples. This variation was observed in all of the tests for the five sample materials but was less pronounced in the curves for the GPS and GRS materials. Since these materials had higher coefficients of uniformity than the other materials, it is possible that gradation is a controlling factor in repeatability of preparation efforts.

Tables IV and V were used to analyze the relationships between physical properties of materials and subsidence. The relative densities obtained by consolidation could not be used for direct comparison to physical properties in the form as presented in Table V. Therefore, a curvilinear regression analysis was performed for each material to determine the relationship between relative densities and subsidence. The statistical model used to perform the regression analyses was based on a least square method using a transformed system of linear equations. The specific model chosen was an exponential curve in the form of

TABLE V

RELATIVE DENSITY PRIOR TO SUBMERSION AT VARIOUS CONSOLIDATION PRESSURES

Material Code	Initial D_R = 17%			Initial D_R = 36%			Initial D_R = 62%		
	0.25*	1.00	4.00	0.25	1.00	4.00	0.25	1.00	4.00
HHD	20.69	23.59	24.48	37.32	42.37	47.93	63.71	67.02	69.55
CAC	18.87	20.61	27.11	(Tests discontinued after 0% subsidence for CAC)					
CAA	19.75	21.65	29.10	37.56	42.17	50.90	63.58	66.95	74.83
GPS	20.52	26.37	44.33	37.09	41.20	54.92	63.11	65.68	71.57
GRS	19.54	41.28	52.45	37.62	46.48	65.24	63.26	65.81	74.60

*Consolidation Pressure in Tons per Square Foot

$$y = ae^{bx} \tag{7}$$

where a and b are regression coefficients and e is the base of natural logarithms. By substituting the symbols D_R for x and s% for y, the general form of the equation for relative density with respect to subsidence becomes

$$s\% = ae^{bD_R} \tag{8}$$

Regression coefficients were calculated with the aid of a digital computer and a program obtained from the Hewlitt-Packard Company. The accuracy of the relationships thus obtained was determined by the coefficient of determination for the curve fit. Coefficients of determination obtained for the curves developed for all materials with the exception of HHD indicated that the use of an exponential equation to represent the relationship between relative density and subsidence is valid.

5.3.2 Comparison of Subsidence and Physical Properties

Table VI presents the results of regression analyses for relative density in comparison to subsidence for the various materials tested. Graphical comparisons for these two properties are presented in Figure 8. From the results of the regression analyses, the following equations have been developed for this relationship for each of the materials tested:

$$\text{HHD:}\quad s\% = 0.66\, e^{-0.02\, D_R} \tag{9}$$

$$\text{CAC:}\quad s\% = 4.40\, e^{-0.31\, D_R} \tag{10}$$

$$\text{CAA:}\quad s\% = 0.49\, e^{-0.05\, D_R} \tag{11}$$

TABLE VI

REGRESSION CURVE INTERCEPTS FOR SUBSIDENCE AND RELATIVE DENSITY

D_R	HHD	CAC	CAA	GPS	GRS
10	0.52	0.19	0.30	3.15	14.50
20	0.42	0.01	0.18	1.50	8.50
30	0.33	$3.0\text{X}10^{-4}$	0.11	0.72	5.08
40	0.26	---	0.07	0.34	3.01
50	0.21	---	0.04	0.16	1.78
60	0.17	---	0.03	0.08	1.05
70	0.13	---	0.02	0.04	0.62
80	0.11	---	0.01	0.02	0.37
90	0.08	---	0.005	0.01	0.22

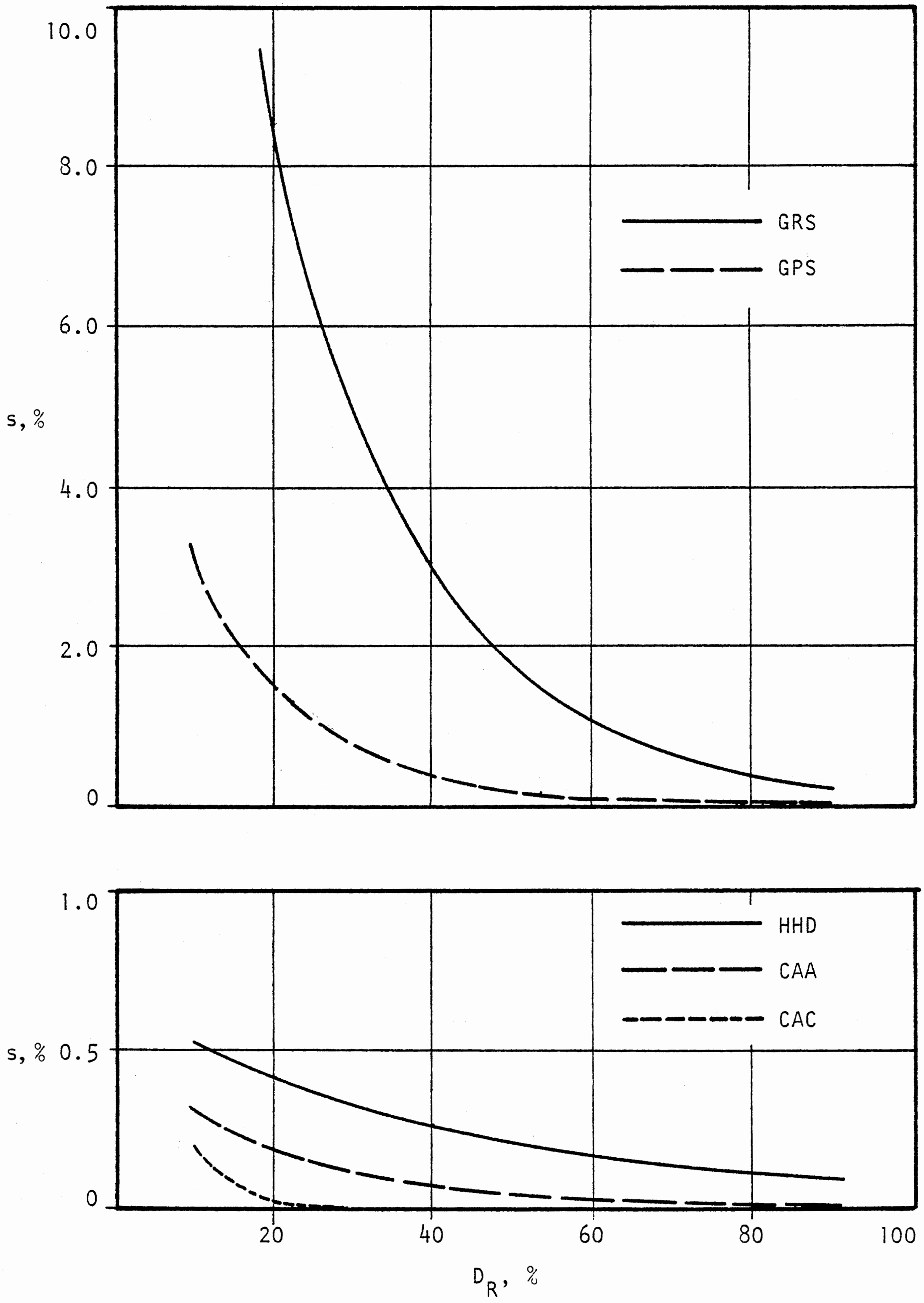

Figure 8. Percent Subsidence With Respect to Relative Density

$$\text{GPS:} \quad s\% = 6.59\, e^{-0.07\, D_R} \tag{12}$$

$$\text{GRS:} \quad s\% = 24.51^{-0.05\, D_R} \tag{13}$$

The relationship between subsidence and coefficient of uniformity was evaluated for conditions of relative density conforming to 30 percent, 50 percent, and 70 percent. It was found that by deleting the values obtained for the HHD sand, good correlations were obtained for the relationship for the remainder of the materials. Figure 9 demonstrates these relationships and indicates that subsidence potential increases with coefficient of uniformity. It is interesting to note that materials with high coefficients of uniformity have a potential for subsidence at a relative density of 70 percent. This value of relative density is generally considered to be the point at which a soil is stable with respect to liquefaction potential.

By eliminating from consideration those materials which are most influenced by high coefficients of uniformity, the relationship may be established between subsidence and median particle diameter. This relationship is shown in Figure 10 for HHD, CAA, and CAC materials at three conditions of relative density. This figure demonstrates that subsidence potential increases with a decrease in medium particle diameter.

Comparisons between subsidence potential and particle shape were not made for this study. This was a result of the narrow range of sphericity determined for all materials. Roundness, or angularity, of particles could be an influencing factor with respect to subsidence. To properly evaluate this relationship, samples having different values for angularity but essentially similar gradations would have to be tested.

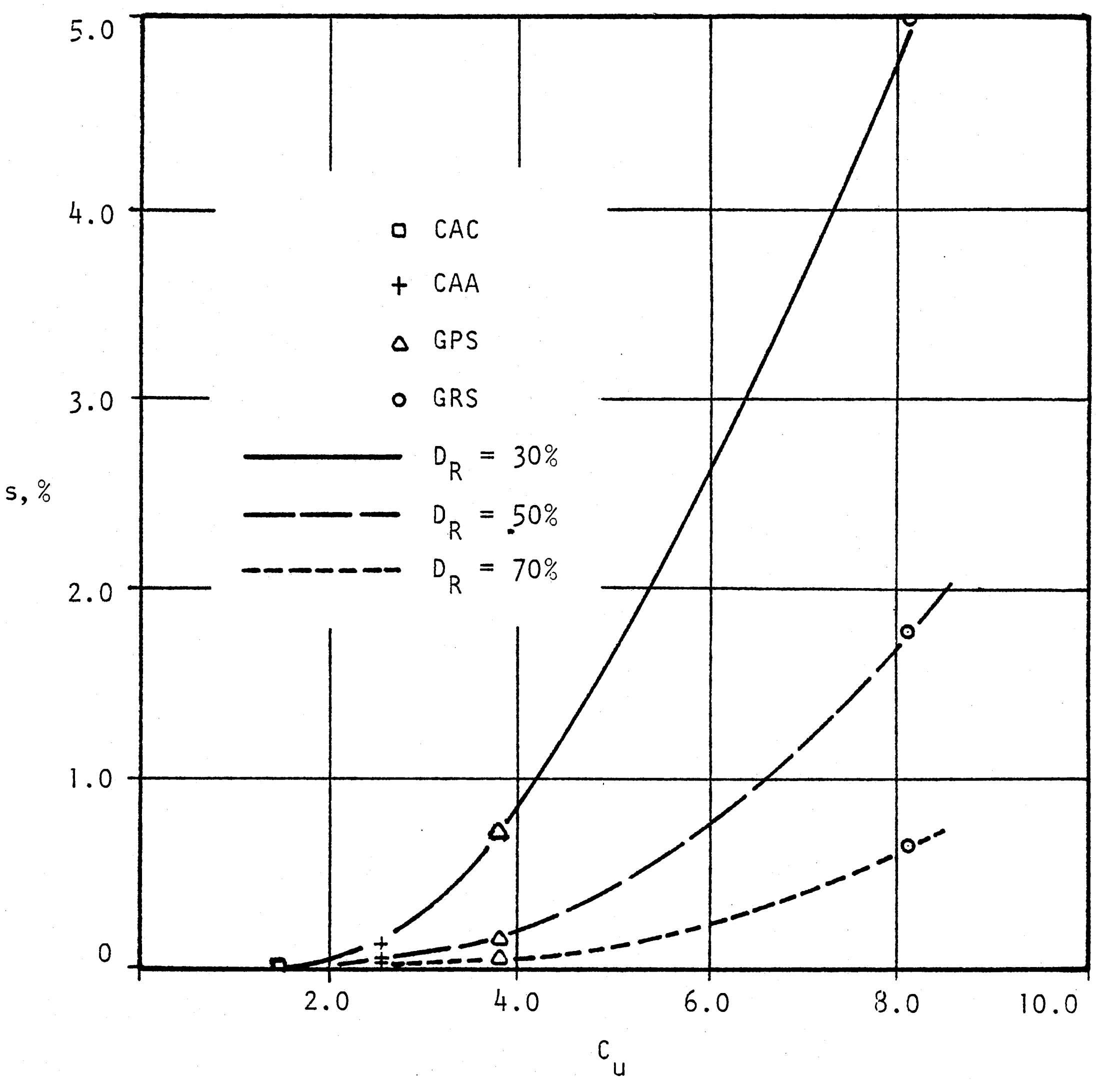

Figure 9. Percent Subsidence With Respect to Coefficient of Uniformity

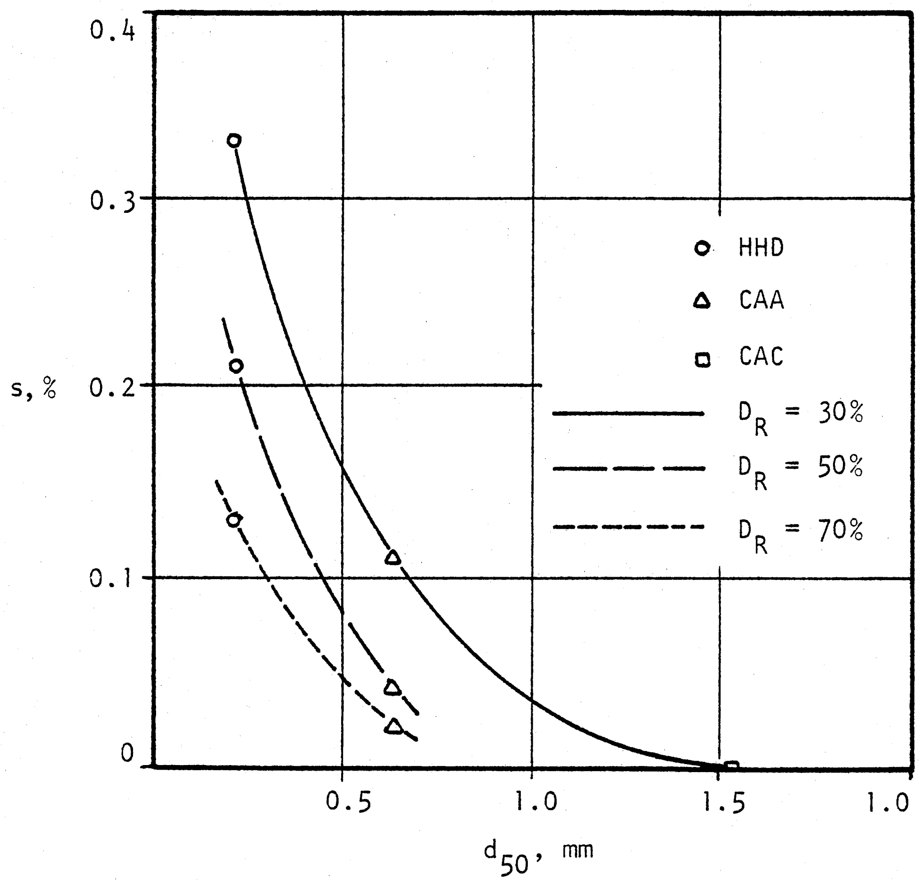

Figure 10. Percent Subsidence With Respect to Particle Size

5.3.3 Subsidence Mechanisms

An investigation of subsidence mechanisms was not one of the objectives of this study. However, a brief discussion of the behavior of the particular materials used upon flooding is in order. The extremely low subsidence, at low relative density and vertical pressure observed for CAC demonstrates the effect of particle diameter on subsidence potential. In this case, the resistance to subsidence is explained by interparticle stresses at points of contact. It can be demonstrated that for a mass of material with a given volume, the stress at contact points is greater in materials with larger particle diameters than in finer media. The reason for this is that the number of points in contact in a given volume decreases with an increase in particle diameter. Therefore, the external stress applied to the mass is distributed over fewer transfer points which in turn causes higher interparticle stresses and a corresponding increase in resistance of particle displacement from external loading.

The subsidence observed in the remainder of materials used in this study may be explained by two possible mechanisms. The first of these has been observed and recorded by many researchers. This involves the removal of tensile stress between particles induced by capillary tension. This mechanism does not account entirely for the subsidence observed. In calibrating equipment for this study, tests were performed on oven dry materials of HHD. Significant subsidence was observed upon flooding this material at a consolidation pressure of 4.00 TSF.

Hydraulic gradients were maintained at sufficiently low values to prevent removal of particles from samples during testing. With the elimination of this factor as a possible cause for subsidence other than interparticle tension, there remains another mechanism to be investigated to explain subsidence. It is postulated that this mechanism has to do with progressive reorientation of particles upon flooding. If a few small particles were to become dislodged from their original positions upon application of water, it is likely that adjacent particles could occur to the extent necessary to affect a major portion of the volume of material tested.

CHAPTER VI

APPLICATIONS AND CONCLUSIONS

6.1 Applications

6.1.1 Analytical Uses

The procedures described herein may be used as an analytical tool to predict subsidence of granular media for specific applications. Such applications may include the prediction of subsidence in hydraulic structures such as earth filled dams with granular filter material. Another use is the prediction of subsidence of structures located on sand deposits susceptible to an increase in ground water elevation. In using the methods of this study for analysis of natural soil deposits, the inability to place undisturbed materials with natural structures intact into the consolidation ring presents a problem. This can partially be overcome on clean sands by placement of material in the consolidation ring in a remolded condition at the same state of density and moisture content as occurs in the field. Vertical stress conditions can be accurately duplicated in the laboratory and weight of flooding can be controlled to that expected for field conditions. Because of the problem of sample disturbance, the predictive art at present may not provide accurate results. However, a potential range of magnitude of subsidence can be determined.

6.1.2 Construction Uses

Applications of the methods developed for construction are limited. The reason for this, simply stated, is that the magnitude of subsidence upon flooding of sands is far less than many in the construction industry have anticipated to this time. One potential use in construction may be the inducement of pre-subsidence in natural sand deposits subjected to flooding. This procedure would be analogous to the use of a surcharge fill for preconsolidation of fine grained deposits. The methods of applying water to create the subsidence would have to be investigated in detail. It is believed that few individuals that recommend flooding of materials for consolidation recognize the quantity of water that is required for complete saturation. Also, there is the problem of the method of application of water. Water applied at the ground surface would have to be ponded for a period of time and in sufficient quantity to provide the necessary saturation. Because of the volume of water required the use of dikes to create a pond would be required for deposits with thicknesses greater than one or two feet. It may be possible to induce subsidence beginning at the bottom of a sand deposit by the injection of water with methods similar to those used for grouting. The benefit of this method would be the avoidance of air pockets within the mass and a more complete densification of the material.

6.2 Conclusions

6.2.1 Magnitude of Subsidence

The magnitude of subsidence of sand upon flooding is low with values generally less than one percent of the height if the sand layer. The exception to this may be found in materials that are well graded with high coefficients of uniformity. Although of low value, there is a potential for subsidence of granular materials at relative densities which have been considered indicative of stable conditions. The magnitude of subsidence potential caused by flooding is variable for different materials and is dependent upon material properties.

6.2.2 Relationships

Relationships have been defined which indicate the response of a granular mass to flooding in comparison with physical properties. For the materials tested, relationships have been developed for subsidence with respect to coefficient of uniformity, relative density and particle size. The decrease in subsidence with increasing relative density has been demonstrated to be an exponential function. Equations for this relationship have been presented for the materials used in the analyses. It has been demonstrated that subsidence potential increases exponentially with an increase in coefficient of uniformity. A determination has been made to the effect that increasing particle diameter corresponds to decreases in subsidence.

6.2.3 Methods

The methods of testing and analysis described in this study are applicable for use in the prediction of subsidence magnitude for granular media which may experience submersion. Testing methods used are repeatable in any geotechnical laboratory with a capability for consolidation testing and relative density determinations. The procedures described may be used for any condition of in-place relative density and any desired magnitude of vertical induced stress.

6.3 Future Research

6.3.1 Sphericity and Roundness

Additional research is needed to determine the effects of particle shape on subsidence potential. This recommendation is made because for certain materials these properties may have effects greater than those reported for particle size and coefficient of uniformity. In a given group of sands of similar uniformity and particle size, the effect of particle shape could be the single variable.

6.3.2 Various Materials

Prior to the establishment of a general body of knowledge on this topic, a wide range of material types must be investigated at various conditions of relative density and induced stress.

6.3.3 Three Dimensional Strain

The concept of saturation induced subsidence should be expanded to include consideration of the effect of volumetric strain induced by intermediate and minor principal stresses as well as the major principal stress. For these investigations, methods may be developed using conventional triaxial testing equipment.

6.3.4 Boundary Conditions

The effect of boundary restraints upon subsidence potential must be investigated for application of the principles described herein. Types of boundary restraints that may influence the subsidence potential of a deposit of granular material include the frictional resistance between a sand backfill and different materials at the plane of contact and the effects of an impervious overburden confining a sand deposit with a potential for subsidence.

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