Distribution and Engineering Significance of Sediments Bordering the Mississippi From Donaldsonville to the Gulf.

Charles Rudolph Kolb
Louisiana State University and Agricultural & Mechanical College

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Louisiana State University, Ph.D., 1962
Geology

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DISTRIBUTION AND ENGINEERING SIGNIFICANCE OF SEDIMENTS BORDERING THE MISSISSIPPI FROM DONALDSONVILLE TO THE GULF

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Geology

by

Charles R. Kolb
B.S., Louisiana State University, 1947
M.S., Louisiana State University, 1949
January, 1962
Errata Sheet

DISTRIBUTION AND ENGINEERING SIGNIFICANCE OF SEDIMENTS BORDERING THE MISSISSIPPI FROM DONALDSONVILLE TO THE GULF

1. Page 3, line 2, ref 19,51 should be 19,47.
2. Page 15, last line, ref 10 should be ref 38.
3. Page 29, 10th line, northeast should be northwest.
4. Page 30, 2nd-to-last line, ref 10 should be ref 53.
5. Page 38, line 19, plate 3 should be plate 11.
6. Page 39, fig. 7 caption, plate 3 should be plate 11.
7. Page 66, line 9, plate 9 should be plate 8.
8. Page 66, line 10, vegetive should be vegetative.
10. Page 114, reference 28, Lopik, J. R., Van, should be Van Lopik, J. R.
11. Plate 1, Bonne Carre should be Bonnet Carre.
The ever-increasing rate of industrial and cultural development along the banks of the Mississippi River between Baton Rouge, Louisiana, and the Gulf of Mexico during the past two decades has focused national attention on the economic potential of this lower 230 miles of the river. Among the more obvious advantages of the region are its bountiful supply of natural hydrocarbons and the river, which serves both as an artery for cheap transportation and a source of tremendous quantities of fresh water. Disadvantages include poor foundation conditions of the soils which have formed in the very recent geologic past and, again, the river—in this instance because of its flood potential. One of the major responsibilities of the U. S. Army Corps of Engineers is to minimize the danger of flooding, and it is safe to say that engineering developments have progressed to the point where such a danger is only a very remote possibility. Planning, building, and maintaining its flood control, navigation, and bank stabilization projects require that the Corps have readily available data of various kinds on this lower reach of the river. Among the most important of these data is an adequate knowledge of the soils which compose the bed, banks and near-bank areas, and of the engineering significance of these soils.

This study is an outgrowth of this need. An investigation of an area several miles on either side of the river between Donaldsonville, Louisiana (50 miles downstream from Baton Rouge), and the Gulf was
sponsored by the New Orleans District, Corps of Engineers (NOD). Data
collection began in 1959. Logs of soils borings were collected from the
files of the Geology Branch, Waterways Experiment Station (WES), Vicks­
burg, Mississippi, from the New Orleans District, from the Groundwater
Division, U. S. Geological Survey (USGS), Baton Rouge, Louisiana, from
the Coastal Studies Institute, Baton Rouge, Louisiana, and from other
government and private sources. Thirty-two drive-sample borings were
made by the NOD in areas specially selected by the writer specifically
for this study. In addition, about 30 auger borings were made by the
USGS in areas selected jointly by the USGS and the writer.

The writer is grateful to the many people who supported this under­
taking. He is particularly grateful to the New Orleans District for
sponsoring it; to Colonel Edmund H. Lang, former Director of WES, who
encouraged the writer's taking a year's leave-of-absence from his duties
as Chief of the Geology Branch, Soils Division, WES, to meet necessary
scholastic commitments in residence at Louisiana State University; and
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of the Soils Division, WES, who approved the duty assignment and other­
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The writer is also grateful to Drs. James P. Morgan and B. J.
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Thanks, and something more tangible, are due the writer's wife, Bertha, and his young son, Chuck, for their understanding, patience, and moral support.
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ABSTRACT

The ever-increasing rate of industrial and cultural development along the banks of the Lower Mississippi River during the past two decades has focused attention on the economic potential of this region of the United States. Industrial site construction; planning, building, and maintaining flood control and navigation structures; and bank stabilization projects require an adequate knowledge of the soils which compose the bed, banks and near-bank areas of the river, and of the engineering significance of these soils. This study considers the engineering soils within an area several miles on either side of the river from about Donaldsonville, La., to the Gulf, a distance along the river of 189 miles. Soils in this region consist principally of Recent deltaic plain deposits overlying an eroded and oxidized Pleistocene shelf at fairly shallow depths. Most foundation problems involve a determination of the depth to this Pleistocene horizon and a separation of the Recent sediments above into environments of deposition with significantly different lithologies and engineering properties.

Approximately 1000 borings were available in the study area and an additional 60 borings were made specifically for the study. The distribution of surface depositional types was mapped, the Pleistocene contoured, and important environments buried beneath shallow surficial soils, such as point bar deposits and abandoned courses and distributaries, were delineated. Distribution of depositional environments, and
their associated types and engineering properties are shown in 32 detailed cross sections. This study relates the geologic interpretation of riverbank soils to typical problems of earthwork design and briefly considers the effect of these sediments and other geologic factors on river migration.

Significant points learned in this investigation include the following:

a. The Mississippi River flows across a "shelf" of shallow Pleistocene deposits between College Point (river mile 157) and English Turn (river mile 78). This shelf is far less dissected than was thought heretofore. The depth to this horizon between the two points mentioned varies from 0 to 150 ft.

b. The concept of backswamp deposits underlain by coarse substratum deposits loses its usefulness in interpreting logs of borings downstream from College Point. Instead, boring information must be interpreted solely in terms of environments characteristic of the deltaic plain.

c. Point bar deposits form fairly significant wedges of sediment flanking the river as far downstream as New Orleans. Only minor point bar areas occur between New Orleans and the Gulf. No trend toward a decrease in grain size in a downstream direction was noted in the point bar deposits. An expected slight increase in grain size with depth was noted. Point bar deposits consisting almost entirely of silt are found in some areas. The fineness of the deposit, its position with respect to the more characteristic sandy point bar, and the tight curvature of the meander scars left by these deposits suggest that they are older deposits left by a smaller stream than the present Mississippi.
d. The existence of a well-defined buried beach trending through the New Orleans area has been fully confirmed and its extent and thickness mapped.

e. Prodelta clays form a homogeneous wedge of fine-grained sediment encountered at a depth of -40 ft msl in the New Orleans area and at -90 ft near Head-of-Passes. The unit thickens from approximately 40 ft to 140 ft within the same distance.

f. River migration is most noticeable between river miles 189 and 156 where the river is migrating into substratum sands, backswamp clays, and silty point bar deposits. It is less rapid where it must cut its channel into the Pleistocene deposits between river miles 156 and 78. Migration of bends between Donaldsonville and the Gulf averages less than 2 ft per year. There is no reason to believe that the rate of river migration in the lower river will increase markedly from the very slow rate which has characterized it in the past.
CHAPTER I
INTRODUCTION

One of the most important services the geologist can perform for the soils engineer is to interpret the samples or logs of the many borings made for engineering projects. Such interpretations must be based on a conviction of the orderliness of natural geologic and sedimentary processes and a knowledge of how these processes operate. Exploration of all the intricacies of stratification at a project site is usually impracticable or impossible; natural conditions must therefore be determined through inference, and the best generalization of soils conditions made from available evidence. The accuracy of these generalizations depends on the amount of evidence observed and the validity of the inferences drawn. Each boring made for a foundation investigation is another bit of evidence, and since each costs money, the wise engineer learns to value the geologist specifically for the inferences he is able to make and the amount of data he needs to make them.

Delineation of subsurface conditions in the deltaic plain of southeast Louisiana has gradually progressed from blind correlation between borings to progressively more valid interpretations based on geologic inference. Geologic studies\(^{14,15}\) in the 1940's developed the

\(^{*}\)Raised numbers refer to similarly numbered entries in the list of selected references at the end of this report.
general history of the Mississippi Alluvial Valley and devised a comprehensive classification for these environments of deposition characterizing the middle and upper portions of the valley. This classification has been developed and used to excellent advantage in interpreting engineering soils* since that time. The terms point bar, braided stream deposit, swale, clay plug, etc., some of which were introduced into the literature by these references, are now widely accepted and the recognition of these environments is a requisite for the proper engineering and geologic interpretation of borings. In southeast Louisiana, these early studies established the fact that an ancient horizon—the Pleistocene—with relatively high strength characteristics underlies the normally softer wedge of Recent sediments, but the sediments were collectively classed as deltaic plain soils.

Little further work was done on the deltaic plain deposits in the 1940's, but early in the 1950's many advances were made in recognizing

*Soil, as an engineering term and as used throughout this text, may be defined as a naturally occurring accumulation of uncemented, or loosely cemented, inorganic and/or organic materials. Reference further states that soil "can be separated by mechanical means, such as agitation in water." From the standpoint of the engineer, therefore, the term soil is used to distinguish between materials that are indurated or cemented (rock) and those that are not, regardless of where or at what depth below the surface these materials occur. The validity of this definition is only partially substantiated by Webster's Unabridged which defines soil as "The surface earth of a particular place with reference especially to its composition or its adaptability to the ends of the farmer, builder, engineer, etc."

The term has been used for a much longer period of time in the sense generally accepted by the agronomist, the geologist, and other scientists, i.e., the surficial unconsolidated mantle of earth material which has been altered by physical, chemical, and biological agents to such an extent that it will support rooted plants. Use of this definition in the study area leaves much to be desired. Much of the alluvial, deltaic, and marine sediments involved are so recent in origin that there has been little time for chemical, physical, or biological alteration to depths greater than several inches.
and delineating some of the many environments of deposition that make up this enormous wedge of sediment.\textsuperscript{19,51} Names such as prodelta deposits and interdistributary clays were introduced into the literature. In 1958 the U. S. Army Engineer Waterways Experiment Station (WES) published a report\textsuperscript{53} which described and classified the deltaic plain environments from the standpoint of their associated engineering soil types. Only those environments forming volumetrically significant and characteristically different units of soil were described and classified. Established nomenclature was used wherever possible in this classification and some new terms, e.g., intradelta deposits, were introduced.

This classification was based partially on a previously published report which interpreted borings made for the Gulf Outlet Channel,\textsuperscript{52} and its validity and utility are substantiated in the present study. In general, the basic concepts involved in this classification of environments are well justified. Only a few soils conditions encountered in the many borings made or collected from other sources and analyzed for this study did not fit these basic concepts. There were some instances where anomalous conditions were found, however; e.g., the occurrence of clay units where the present concept of deltaic plain formation dictated that only coarser materials should exist, or the presence of low-strength soils where only high-strength soils should be expected. It is inevitable that this should be so. We have a great deal to learn concerning the methods and sequence of deposition in the deltaic plain. Nevertheless, studies such as this one enable the geologist to reconstruct systematically the complicated history of deltaic plain deposition. They permit him to strengthen his conviction and inferences in some areas and to discard erroneous concepts in others. They permit a
reconstruction of soil conditions between often widely spaced borings based on increasingly sound inference rather than blind correlation of soil types between borings. They suggest sound working hypotheses based on geologic origin or environment to explain radical variations of engineering properties in soils which otherwise appear to be similar. As Terzaghi and Peck\textsuperscript{43} point out, "Two clays with identical grain-size curves can be extremely different in every other respect. Because of these conditions, well-defined statistical relations between grain-size characteristics and significant soil properties such as the angle of internal friction have been encountered only within relatively small regions where all the soils of the same category, such as all the clays or all the sands, have a similar geological origin."

The primary purpose of the present study is to map the engineering soil types in the immediate vicinity of the river from the vicinity of Donaldsonville, La. (plate 1), to the Gulf of Mexico and to show their distribution in plan and profile. This has been done in plates 3-39. The text (a) outlines the physiography, the cultural development, and the most recently reconstructed geologic history of the study area; (b) describes the distribution and the physical and engineering characteristics of the sediments; (c) relates the geologic interpretation of riverbank soils to problems of earthwork design; and (d) briefly considers the effect of these sediments and other geologic factors on river migration.
CHAPTER II

PHYSIOGRAPHIC SETTING AND CULTURAL DEVELOPMENT

General Physiography

The area under consideration in this study is that part of south-eastern Louisiana bordering the Mississippi River between river miles 189 and 2 (above Head-of-Passes), or from 16 miles upriver from Donaldsonville, La., to Head-of-Passes (plate 1). Topographically, the area is one of negligible relief. Highest elevations are found closely adjacent to the present river channel and reach 30 ft msl upstream from Donaldsonville. Lowest elevations are in artificially protected areas and natural depressions in the marsh or swamp. Elevations of -6 ft msl are recorded in certain portions of New Orleans. Normally, such depressions are filled with water and form the myriad lakes and shallow bays which characterize the vast, flat, near-sea-level marshlands of south-east Louisiana.

Topographic features of paramount importance are the natural levees which flank the present course, abandoned courses, and distributaries of the Mississippi River. The natural levees slope gently from crest to toe, varying in width from one-quarter to five miles. A natural levee with a crest of 25 ft msl near Donaldsonville typically slopes to 5 ft msl in a distance of 4 miles. The slope is concave upward, flattening with distance from the river. The area between the 5 and 10-ft contour is usually as great as that between the 10- and 25-ft contour. At the
landside toe the natural levee grades imperceptibly into the marsh or swamp. Hardwood forests characterize the swamps and once covered most of the natural levee areas; grasses and sedges and small bodies of open water are typical of marsh. Cultivation is confined almost exclusively to the high, well-drained natural levees. Drainage and reclamation of swamp areas, in some instances, extend the cultivated areas beyond the limits of the natural levees.

Prior to the construction of artificial levees, the natural levees were being extended both laterally and vertically by natural river processes. Such extension was probably very slow except in the extreme lower reaches of the river where new natural levees were being formed along the distributaries. But as these new terminal levees formed and the channel was extended, stage variation at a given point upstream increased slightly and the height of the natural levee kept pace, the height adjusting to flood heights. During floods, muddy water would seek out a slight topographic low in the confining natural levee and a shallow crevasse would form. In other instances, lengthy stretches of the natural levee would be inundated with only a few elongate islands remaining above the floodwaters to mark the highest portions of the natural levee. This permitted gradual alluviation of the natural levees and, as floodwaters subsided, crevasses were filled and the height once more adjusted to flood height. Countering this process were gradual subsidence brought about by compaction and regional sinking of the land surface beneath the levee, and the erosion of the levee slope by rainfall. The result of these opposing processes was a balance between levee height and width and the height of floods.

The construction of artificial levees has interrupted these natural
processes. Natural levees are no longer overtopped by floods and landward extension of these ridge areas has ceased. The soil underlying the natural levees continues to consolidate and the weight of the artificial levee locally increases the rate and amount of this consolidation. Drainage projects designed to extend the arable land beyond the toe of the natural levee have lowered the water table, causing additional subsidence. Rainfall continues to erode the natural levees and the material carried away by erosion is not replaced by sediment-laden floodwaters. The net result is the lateral growth of the swamp and marsh environments and the gradual narrowing of the natural levee.

The River

The Mississippi River is narrow and deep from Donaldsonville to Head-of-Passes. Its width seldom exceeds three-quarters of a mile. A maximum depth of -208 ft msl at Fort Jackson (plate 1) near Head-of-Passes was recorded in a 1949-52 survey. Other low points in the river include elevations of -202 ft msl at Bonnet Carre (plate 1) and -204 at mile 60. Minimum thalweg depths average 60-70 ft. Generally, the river becomes progressively less sinuous from Donaldsonville to New Orleans and is almost straight after rounding English Turn just downstream from New Orleans. Migration of the bankline based on historic surveys has been very slow. Early river surveys map a feature called Claiborne Island at river mile 189 (the upstream limit of the study area-- plate 3). This island once had the distinction of being the farthest downstream of any in the Mississippi. At the time of the 1895-96 survey it had been incorporated in the bar at the upper end of Philadelphia Point and what is now the last downstream island in the Mississippi, Bayou
Goula Towhead, began to form at river mile 195.

Stages on the Mississippi vary from 37 ft msl to 1 ft msl at Donaldsonville, from 20 to -2 ft msl at New Orleans, and from 10 to -2 ft msl at Fort Jackson near Head-of-Passes. Discharge at New Orleans varies from a minimum of 79,000 cfs, to 600,000 cfs at normal stages, to 1,250,000 cfs at a river stage of 20. It is estimated that, with the Morganza and Bonnet Carre Floodways above New Orleans in operation, the maximum river stage at that city can be limited to 20 ft msl.

Materials carried in suspension are estimated as 544 million tons annually. Quantities of bed load carried to the Gulf are variously estimated as from 2 to 25 per cent of suspended load volumes.

A salt-water wedge enters the river during low river stages, and the tidal effects have been reported as far upstream as 35 miles above Baton Rouge during extreme low water. At a discharge of about 800,000 cfs the fresh-water currents have sufficient force to completely eliminate the salt-water wedge from the river channel and from all but the extreme seaward end of the passes.

**Artificial Levees**

According to Elliott, the first artificial levee on the Lower Mississippi River was built at New Orleans. The city was founded in 1717 by Bienville who selected the site despite the objections of his engineer, De La Tour, who predicted periodic inundation during floods. De La Tour undertook construction of the first levee and completed the project in 1727. The levee was 5400 ft long, 3 ft high, and 18 ft wide at the top. Contrast this with the present levee upstream from New Orleans which is in some places 30 ft high and close to 5000 sq ft in cross-sectional area.
By 1735 the levee lines on both sides of the river extended from about 30 miles above New Orleans to a point approximately 12 miles below the city, and by 1812 the levee system on both sides of the river had been extended to Baton Rouge on the left bank and beyond that on the right. Crevasses through these levees were a common occurrence during these earlier years. With the completion of more and larger levees, flood stages reached new heights. New Orleans was inundated several times and there was considerable concern that the river bed was being silted in between the levees. It was soon recognized, however, that these new flood heights were a natural result of confining the river between levees. Where once the river had been allowed to spread out at will across the natural levees, thereby lowering stages, it was now confined to a narrow zone between the artificial levees. River depths remained essentially constant.25

Crevasses, too, changed in character. Those occurring through the natural levees had carried waters at relatively low velocities down gentle, natural-levee backslopes. They often spilled thin sheets of water over miles of natural levee. Artificial levees impounded waters to greater heights and on being ruptured—as they often were—permitted water to rush through narrow openings at high velocity, digging scour pools from the crest and spreading the material out in large fans on the landward sides of the natural levees. A major factor in the widening of natural levees after the construction of the artificial levees was these crevasses, and crevasse fans are a common physiographic feature along the lower river.

In 1858 the levees on both sides of the river extended as far downstream as Pointe à la Hache (plate 1). Levee construction and
maintenance deteriorated during and subsequent to the Civil War. With the creation of the Mississippi River Commission in 1879, however, a new era in levee construction and maintenance began. Between 1874 and 1882 all levee lines were repaired, and levees extended as far south as Fort Jackson on both sides of the river. The levees have since been extended to about 10 miles above the Head-of-Passes on both sides of the river.

In 1915 a disastrous Gulf storm occurred at a time peculiarly favorable for damage to the levees below New Orleans, as the river was at bankfull stage below that city. Waves broke over the levees with sufficient volume to carry boats and drift logs completely over them. Wooden wave-wash fences and concrete facing placed on the levees for their protection were destroyed or damaged. A total of about 18 miles of levee were practically obliterated, and about 95 additional miles of levee were damaged.\(^{12}\)

The flood of 1922 caused apprehension for the safety of New Orleans, and as a result a relief outlet was constructed by the removal of the left bank levee from just below Pointe a la Hache to Buras or roughly between river miles 45 and 25. Siltation in this outlet is rapidly destroying its usefulness. Crevasses continued to plague the lower river until the early 1920's. The last crevasses occurred, or were made artificially to alleviate flood flows, in 1927. Fig. 1 is based on Elliott\(^{12}\) and shows crevasses occurring between Baton Rouge and the Gulf in the 1900's. Plates 3-10 show more detailed locations of some of these crevasses and some of the major crevasses prior to that time.\(^*\)

\(^*\)An apparent discrepancy between Elliott's data shown in fig. 1 and data shown on quadrangle maps occurs at the bend just downstream from New Orleans. Poydras crevasse as shown on the St. Bernard quadrangle and in plate 7 is labeled Mon Plaisir crevasse by Elliott. Elliott shows Poydras crevasse as having occurred on the north side of the bend.
Fig. 1. Crevasses occurring on lower river since 1903 according to Elliott\textsuperscript{12}
CHAPTER III
GEOLOGIC HISTORY

Situated in the Mississippi River deltaic plain near its northern margin, the area under consideration is composed primarily of sediments of Recent origin. These sediments, representing deposition under environments ranging from fluvial to marine, are part of a seaward-thickening wedge which overlies the Pleistocene Prairie formation. According to Fisk,\textsuperscript{13} this is the youngest of four Pleistocene terraces in Louisiana, each resulting from deltaic deposition during inter-glacial periods. The Prairie formation is generally accepted as being pre-Late Wisconsin in age and was originally estimated to be 70,000 to 100,000 years old.\textsuperscript{14}

The Prairie formation lies buried beneath Recent sediments throughout most of the study area, at depths ranging from near msl in the northern portion of the area to approximately 600 ft below msl near Head-of-Passes. It does outcrop at the surface, however, in the extreme northwestern part of the study area (about five miles north of Donaldsonville) in the form of a generally east-west trending, coastwise terrace (see fig. 3 and plate 3). Both the terrace and the buried surface slope toward the south or southeast at approximately 3 ft per mile.

In order to understand the events which led to the onlapping and burial of the Prairie surface by Recent sediments as well as the nature
of these sediments themselves, it is necessary to review the Recent postglacial sea level rise. Although a rise in sea level accompanying the retreat of the Wisconsin ice sheets is generally accepted in principle, its duration and magnitude are still quite controversial.

As a result of initial investigations in the Lower Mississippi Valley, it was concluded that sea level at the glacial maximum (about 40,000 years ago) was at least 400 ft below its present stand, and that it steadily rose and achieved its present level about 5000 years ago. A maximum low stand of about -450 ft is now generally recognized but dates varying from 18,000 years to more than 35,000 years have been advanced for this stage.

Recent interpretations of late Quaternary events in south Louisiana and the Gulf Coast region have been presented by McFarlan, Broecker, and Curray. McFarlan's ideas are based on an analysis of C-14 dates of 117 samples taken from the Recent and 5 samples from the Pleistocene. He postulates that sea level was 450 ft below present msl prior to 35,000 years ago. As the ice sheets melted and retreated northward, sea level is believed to have risen to -250 ft msl at some time prior to 35,000 years ago. According to McFarlan, sea level remained at this elevation for at least 18,000 years, then, about 18,500 years ago, ice began to retreat once more and sea level began a new rise (fig. 2).

Broecker and Curray do not agree with the hypothesis of the 250-ft stillstand of sea level during an 18,000-year interval. Broecker, for example, notes that the front of the mid-continent ice sheet is dated as having advanced from north of Lake Erie to southern Ohio between 25,000 and 18,000 years ago. This implies a drop in sea level during that period, after which the ice sheet began its final retreat and sea level
Fig. 2. Various interpretations of sea level rise with time a relatively uninterrupted rise to its present level. Curray presents evidence gathered from detailed bathymetric studies along the Texas and Mexican coastal shelves to support his arguments. Of particular interest are isolated remnants of cemented beach rock and coquina eight fathoms deep near Freeport, Tex. Shell in this shore line feature are assigned radiocarbon dates of 30,000 years. Based on this and other information, Curray (fig. 2) postulates a sea level only 25 ft below its present level 30,000 years ago. In contrast, Frye and Willman postulate a sea level about 150 ft below present level about 25,000 years ago. According to Curray, soundings and bottom samples show no widespread development of submerged deltas or extensive terraces at the 250- to 300-ft depth range as might be expected if McFarlan's hypothesis is correct. All four investigators are fairly well agreed that the time sea level began its last rapid rise was between 18,000 and 20,000 years ago. McFarlan believes this rise began from a depth of -250 ft msl, the others believe it began from levels ranging from 350 to 450 ft below present msl.
Broecker postulates an abrupt warming in climate about 11,000 years ago and an accelerated rate of rise in sea level since that time. Curray, basing his ideas on radiocarbon dates and distribution of sediment characteristics reflecting current directions and configuration of the Texas shelf as it was 7000 to 15,000 years ago, believes there was a cyclic fluctuation of sea level during that time interval. Frye and Willman's studies, based on glacial advance and retreat, suggest a similar but more pronounced cyclic fluctuation during the same period. The time sea level reached its present stand, according to these sources, varies from 5000 years ago to about 3000 years ago. McFarlan cites evidence to indicate that sea level rose 17 ft during the interval between 5650 and 3000 years ago.

Sedimentation was probably an insignificant factor in the study area prior to the time the sea reached 200 ft below present msl. Most of the area stood high above sea level and erosion was the predominant process. The greatest entrenchment occurred to the west and south. The axis of this entrenchment is shown in fig. 3. Until the sea rose to within 200 ft of its present level, only coarse fluvial materials were being deposited within the deepest portions of this trench. As the sea continued to rise fluvial sediments were undoubtedly reworked and redeposited by marine processes near the ancient shore line, but it was probably not until some 10,000 years ago, when sea level was only tens of feet below its present stand, that marine and fluvial-marine sediments of any consequence were deposited on this old erosion surface. Prominent among the marine environments identified in the subsurface are sand beaches which now lie beneath the waters of northern Lake Pontchartrain and one particularly prominent sand ridge which lies
Fig. 3. Abandoned Mississippi River distributary systems, southeast Louisiana
beneath New Orleans (see fig. 13). Carbon-14 dating of samples from the base of the sand ridge in New Orleans suggests an age of 4500 years. Archaeological studies by McIntire indicate that the bar remained a prominent surface feature, a site of Indian habitation, until 1500-2000 years ago.

The history of fluvial deposition in the study area is closely associated with shifts of the Mississippi River deltas. Fig. 3 shows the position of the major courses and distributaries abandoned by the Mississippi in southeast Louisiana. This figure and the brief reconstruction of delta history which follows are based on references 3, 14, 17, 19, 29, 30, 47, and 53. The oldest delta which may have occupied the region was that associated with the Maringouin course of the Mississippi which McFarlan dates as having been active 5000 years ago. Faint traces of what may be abandoned Maringouin distributaries are found south of Donaldsonville and were probably responsible for the first wave of prodelta clays to have been deposited in the region. The Teche course, occupied about 3800 years ago, was confined to the western part of the valley and the southern part of the deltaic plain. The effect of Teche sedimentation in the area along the river from Donaldsonville to New Orleans was probably negligible. Much of the prodelta clays along the river south of New Orleans, however, are undoubtedly of Teche origin.

The first major advance of the Mississippi River into the study area occurred about 2800 years ago when the river abandoned its Teche and occupied its LaLoutre course. This course corresponds in most respects to the present river position from Baton Rouge to Poydras (plate 1). From there it extended eastward to the vicinity of the Chandeleur
Islands (fig. 3) forming the extensive St. Bernard delta. Major abandoned distributaries associated with the LaLoutre course are the Bayou Metairie system trending northeast through New Orleans, and the Barataria system which flowed due south from New Orleans toward Barataria Bay. The Barataria at one time may have carried all, or at least a significant portion, of the river's entire flow.

Mcfarlan\textsuperscript{29} notes that the carbon-14 age determinations for the Lafourche system trending southeast from Donaldsonville suggest that it was first occupied 1500 and abandoned 600 years ago. In all probability the Lafourche never carried the full flow of the Mississippi. The earliest dates of occupancy of the Plaquemines-Modern system south of New Orleans are about 1200 years ago. The present delta at Head-of-Passes began to form about 450 years ago.
CHAPTER IV
DISTRIBUTION, AND PHYSICAL AND ENGINEERING CHARACTERISTICS OF SEDIMENTS

Presentation of Data

Maps

Surface distribution of sedimentary environments in the study area is shown in plates 3-10 as a gray overprint. None of these environments form truly significant thicknesses of sediment. The thickest is the natural levee which reaches a maximum of some 20 ft. The swamp and marsh types delineated on the landward sides of the levees consist of organic deposits seldom more than 10 ft thick. The boundaries between the natural levees and between the swamp and marsh types are transitional and variable. Local subsidence, regional subsidence, severe windstorms, and cultural improvements affect these boundaries from decade to decade. More significant are the environments which these surface deposits overlie and largely mask. These are shown in black and include (a) the Pleistocene, the surface of which is contoured in feet below mean sea level, (b) the point bar, (c) several buried beaches, and (d) abandoned courses and distributaries.

Data used in the preparation of this report consisted principally of the logs of numerous borings made within the study area. In addition to borings made in the past by the U. S. Army Engineer District, New Orleans, boring logs were available in the files of the Geology Branch,
Waterways Experiment Station, the Coastal Studies Institute, Baton Rouge, La., and from engineering firms, water-well drillers, and seismic companies. This information was supplemented by 32 borings made specifically for the project by the New Orleans District and approximately 30 auger borings made by the Ground-Water Division, U. S. Geological Survey, at Baton Rouge, La. Boring data were freely exchanged between the two government agencies, and geological interpretation was often based on a cooperative effort by geologists from both organizations.

Not all borings available in the files of the Geology Branch, WES, are located in plates 3-10. However, the most reliable, and/or those used as the basis on which interpretations were made, are shown. An exception to this occurs in the New Orleans area. Here boring data are so numerous that only locations of selected borings are included. For locations of many additional excellent borings in this area, see plate 4A of reference 53. So many borings have been made in the New Orleans area during the past several years that it has been impossible to analyze these data and include the results in this study.

Cross sections

Subsurface distribution of sedimentary environments is shown in plates 11-39. Boundaries of the environments, logs of the borings used to delineate these environments, and much of the available engineering information on each of these borings are shown in black. Inferences as to the lateral and vertical continuity of soil types, based on the distribution of the sedimentary environments, are shown in gray. Plates 40-44 contain logs of borings not utilized in sections. Locations of these borings are shown in plates 3-10.
The section legend in plate 2 defines the various symbols, values, and graphic methods used on the logs of borings shown in plates 11-44. Some further explanation is warranted.

Because data utilized in preparing the logs of borings were from different sources, two systems of classification are used: (a) grain size, and (b) the Unified Soil Classification System (USCS). The grain-size classification is based on percentages by weight of sand, silt, and clay-size particles comprising the soil classified. Sand ranges from 1.0-0.05 mm in diameter, silt between 0.05-0.005 mm, and clay is less than 0.005 mm in diameter. The soil is classified according to the soils percentage triangle shown in plate 2. Graphic logs of all borings classified in this manner are shown within dashed borders. It should be pointed out that only occasionally are actual laboratory grain-size analyses available on which to base the soil classification. Most of the time the soils are classified visually. Although experienced observers can often become remarkably accurate in such visual classification, even the most experienced are far from infallible.

Soils in graphic logs of borings shown within solid borders are classified according to the Unified Soil Classification System. This system is used throughout the U. S. Army Corps of Engineers, the engineering establishments of other Department of Defense agencies, the Bureau of Reclamation, various State Highway Departments, many private engineering concerns, and others. A wealth of well-logged data is available from such sources, particularly within the Mississippi Alluvial Valley.

Basically, the USCS divides soils into two groups, the coarser fraction retained on the No. 200 (0.074-mm) sieve and the fines, the
silts and clays, passing the No. 200 sieve. The coarser fraction is subdivided on the basis of grain size and grading. The finer fraction is subdivided chiefly on the basis of its plasticity. Soils are designated in terms of a symbol. Thus, it is correct to refer to a poorly graded sand as an SP soil.

The most commonly used USCS symbols and the soil types based on grain-size classification to which they are generally equivalent are listed below. Absolute equivalence is not implied.

<table>
<thead>
<tr>
<th>USCS Symbol</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>Clay</td>
</tr>
<tr>
<td>CL</td>
<td>Silty clay, sandy clay</td>
</tr>
<tr>
<td>ML</td>
<td>Silt, sandy silt, clay silt</td>
</tr>
<tr>
<td>MH</td>
<td>Inorganic silt</td>
</tr>
<tr>
<td>SC</td>
<td>Clayey sand</td>
</tr>
<tr>
<td>SM</td>
<td>Silty sand</td>
</tr>
<tr>
<td>OL</td>
<td>Organic silt</td>
</tr>
<tr>
<td>OH</td>
<td>Organic clay</td>
</tr>
<tr>
<td>Pt</td>
<td>Peat</td>
</tr>
<tr>
<td>SP</td>
<td>Poorly graded sand</td>
</tr>
<tr>
<td>SW</td>
<td>Well-graded sand</td>
</tr>
<tr>
<td>GC</td>
<td>Clayey sand-gravel</td>
</tr>
<tr>
<td>GM</td>
<td>Silty sand-gravel</td>
</tr>
<tr>
<td>GW</td>
<td>Well-graded sand-gravel</td>
</tr>
<tr>
<td>GP</td>
<td>Poorly graded sand-gravel</td>
</tr>
</tbody>
</table>

Details of the classification system and the various criteria used in the USCS method of identifying soils are given in Chart I for coarse-grained soils, and Chart II for fine-grained soils. Definitions of possibly unfamiliar terms used in Chart I include the following:

**Coefficient of curvature** \( (C_c) \) which is determined from the gradation curve using the following formula:

\[
C_c = \frac{(D_{30})^2}{D_{60}} \times D_{10}
\]

where \( D_{10} \) = grain diameter at 10% passing, \( D_{30} \) at 30% passing, and \( D_{60} \) at 60% passing the No. 200 sieve.

**Coefficient of uniformity** \( (C_u) \) which is determined from the gradation curve using the following formula:

\[
C_u = \frac{D_{60}}{D_{10}}
\]
This coefficient varies directly with the coefficient of sorting \((C_s)\):

\[ C_s = \frac{D_{75}}{D_{25}} \]

<table>
<thead>
<tr>
<th>MAJOR DIVISIONS</th>
<th>LABORATORY CLASSIFICATION CRITERIA</th>
<th>GRADATION OR PLASTICITY</th>
<th>GROUP SYMBOL</th>
<th>TYPICAL NAMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEAN GRAVELS</td>
<td>Less than 5% pass the No. 200 sieve (0.074 mm)</td>
<td>(C_u &gt; 4) and (C_c) between 1 and 3</td>
<td>GW</td>
<td>Well-graded gravels, gravel-sand mixtures, little or no fines</td>
</tr>
<tr>
<td>CLEAN SANDS</td>
<td>Between 5% and 12% pass the No. 200 sieve</td>
<td>(C_u &lt; 4) and (C_c &lt; 1) or (&gt; 3)</td>
<td>GP</td>
<td>Poorly graded gravels, gravel-sand mixtures, little or no fines</td>
</tr>
<tr>
<td>GRAVELS WITH FINES</td>
<td>Between 12% and 50% pass the No. 200 sieve</td>
<td>Double symbol appropriate to grading and plasticity characteristics</td>
<td>GW-GM</td>
<td>Silty gravels, gravel-sand-silt mixtures</td>
</tr>
<tr>
<td>GRAVEL-SAND-MIXTURES</td>
<td>Less than 5% pass the No. 200 sieve</td>
<td>(C_u &gt; 6) and (C_c) between 1 and 3</td>
<td>SW</td>
<td>Well-graded sands, gravelly sands, little or no fines</td>
</tr>
<tr>
<td>SANDS WITH FINES</td>
<td>Between 5% and 12% pass the No. 200 sieve</td>
<td>(C_u &lt; 6) and (C_c &lt; 1) or (&gt; 3)</td>
<td>SP</td>
<td>Poorly graded sands, gravelly sands, little or no fines</td>
</tr>
<tr>
<td>SANDS WITH FINES</td>
<td>Between 12% and 50% pass the No. 200 sieve</td>
<td>Double symbol appropriate to grading and plasticity characteristics</td>
<td>SW-SM</td>
<td>Silty sands, sand-silt mixtures</td>
</tr>
<tr>
<td>Silt-sand mixtures</td>
<td>Atterberg limits of fines below “A” line on plasticity chart</td>
<td></td>
<td>SM</td>
<td>Clayey sands, sand-silt mixtures</td>
</tr>
<tr>
<td>Clayey sands</td>
<td>Atterberg limits of fines above “A” line on plasticity chart</td>
<td></td>
<td>SC</td>
<td>Clayey sands, sand-clay mixtures</td>
</tr>
</tbody>
</table>

Chart I. Unified Soil Classification of coarse-grained soils (based on reference 48)
Poorly graded soils are those having convex gradations, nearly vertical (uniform) gradations, and gradation curves with "humps" typical of skip-graded material. All well-sorted soils are poorly graded.

Well-graded soils which have grain-size distributions that generally plot as smooth and regular concave curves with no sizes lacking or no excess of material in any size range. They are always poorly sorted soils.

Chart II outlines the basis for classifying fine-grained soils.

<table>
<thead>
<tr>
<th>MAJOR DIVISIONS</th>
<th>LABORATORY CLASSIFICATION CRITERIA</th>
<th>GROUP SYMBOL</th>
<th>TYPICAL NAMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than 50% of material is smaller than No. 200 sieve size</td>
<td>Atterberg limits below &quot;A&quot; line on plasticity chart</td>
<td>ML</td>
<td>Inorganic silts, rock flour, or clayey silts with slight plasticity</td>
</tr>
<tr>
<td></td>
<td>Atterberg limits above &quot;A&quot; line on plasticity chart</td>
<td>CL</td>
<td>Inorganic clays of low-to-medium plasticity, gravelly clays, sandy clays, silty clays</td>
</tr>
<tr>
<td></td>
<td>Not applicable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid limit less than 50</td>
<td>Atterberg limits in hatched zone on plasticity chart</td>
<td>ML-CL</td>
<td>Organic silts and organic silty clays of low plasticity</td>
</tr>
<tr>
<td></td>
<td>Atterberg limits below &quot;A&quot; line on plasticity chart with organic odor and color</td>
<td>OL</td>
<td></td>
</tr>
<tr>
<td>Liquid limit greater than 50</td>
<td>Atterberg limits below &quot;A&quot; line on plasticity chart</td>
<td>MH</td>
<td>Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts</td>
</tr>
<tr>
<td></td>
<td>Not applicable</td>
<td>CH</td>
<td>Inorganic clays of high plasticity, fat clays</td>
</tr>
<tr>
<td></td>
<td>Atterberg limits above &quot;A&quot; line on plasticity chart</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atterberg limits below &quot;A&quot; line on plasticity chart with organic odor and color</td>
<td>OH</td>
<td>Organic clays of medium-to-high plasticity</td>
</tr>
<tr>
<td></td>
<td>Highly organic soils identified by color, odor, spongy feel, and frequently by fibrous texture</td>
<td>Pt</td>
<td>Peat and other highly organic soils</td>
</tr>
</tbody>
</table>

Chart II. Unified Soil Classification of fine-grained soils (based on reference 48)
A plasticity chart, needed for the classification, is shown as Fig. 4. Plasticity is measured in terms of Atterberg limits, water content boundaries between the different states in which a soil may exist. The liquid limit is the boundary between the liquid and plastic states. The plastic limit is the boundary between the plastic and semisolid states. The numerical difference between the liquid limit and the plastic limit is called the plasticity index. Limits are determined on the fraction of a soil passing the No. 40 sieve.

As in the case of soils classified according to the grain-size percentage triangle, most of the soils designated in USCS terms in this report were classified visually. Common practice in the New Orleans District is to check visual classifications periodically with laboratory grain-size and plasticity analyses necessary for positive identification. Because so much of the soil in the delta area is fine grained, the New
Orleans District further subdivides the USCS soil types in the manner shown in the table in the upper left portion of plate 2. Note that this subclassification is included immediately to the right of most of the graphic logs of borings of plates 11-44.

Of possible interest is the writer's experience in using the grain-size and the USCS systems of classification. When the USCS came into existence some 10 years ago, it appeared to many that it had a precision and a utility from the standpoint of engineering problems that was commendable, but that it would be impractical for visual classification. Having had about 10 years' experience using both systems, the writer feels this fear is unfounded. The coarser sizes can be estimated as precisely (or imprecisely) in both systems. And since plasticity has always been an index to classification according to grain size, the use of plasticity terms in the USCS requires only that the observer gain some experience in estimating Atterberg limits. An important advantage of the USCS is that where precise classification is desired, plasticity parameters of the fine-grained soils are much more easily and accurately determined in the laboratory than are the grain-size characteristics.

Various soil values are tabulated to the left and right of the graphic logs of borings. Color and consistency are visually classified. A correlation of visual consistency classifications with cohesive strengths is shown in plate 2. Wherever other data are tabulated to the left or right of the graphic log, the values are based on laboratory analyses. Such data include cohesive strengths, effective grain sizes, the unit dry and wet weight or density of the soil, the liquid limit, the plasticity index, the penetration resistance, and percentages of sand or silt sizes within a given sample. The position of the data on
the graphic log indicates that a 6-in. length of sample was taken and classified at that depth. Each of the soil parameters listed above are more fully described in plate 2. A complete definition of these terms can be found in any elementary text on engineering geology or soil mechanics.

Text

In the discussion which follows the Pleistocene deposits are treated as a unit. Discussion of the Recent is divided into the broad categories of fluvial, fluvial-marine, marine, and paludal environments. These are further divided into individual environments of deposition mapped in plan or in profile in plates 3-39. Only those environments identified within the study area are discussed. And, because of the nature of the study, emphasis is placed on those facets of environment development which have greatest effect on stratification and engineering properties of the soils. For a more comprehensive treatment of these and other environments of deposition within the deltaic plain the reader is referred to the WES report Geology of the Mississippi River Deltaic Plain of Southeastern Louisiana.53

The Pleistocene

Boring data collected and analyzed for this study have permitted considerable refinement of the contours on the buried Pleistocene surface, particularly where this surface lies at depths of less than 150 ft. Fig. 5 shows contours on this surface developed from the latest available information. Compare this map with plate 4 of reference 17 (1955) and reference 14 (1944). Noteworthy is the minor amount of dissection which characterizes the shallow shelf of Pleistocene material which
Fig. 5. Contours on top of Pleistocene in feet below mean sea level. Limited data.
...a feet below mean sea level. Broken contours based on very limited data.
slopes southward beneath Lakes Maurepas and Pontchartrain and much of
the deltaic plain of southeast Louisiana. Earlier maps based on fewer
data included numerous deep re-entrants or entrenchments of this shelf.
Erosion during the time of lowered sea level was thought to have
thoroughly dissected it. This does not seem to be the case, because
the shelf is relatively undissected and although locally uneven, major
entrenchments are few in number. Steepest slopes are on the southwest
border of the shelf where the Pleistocene surface drops fairly rapidly
toward the axis of deepest entrenchment, an axis that trends roughly in
a southeast-northeast direction through Houma, La.

Following the rise of sea level after retreat of the Pleistocene
ice sheets and the inundation of the Pleistocene surface with fluvial
and deltaic deposits, gradual subsidence slowly tilted this shelf toward
the south. The tilt of this surface now averages 3 ft per mile. The
only other modification of this shallow shelf has been its entrenchment
by the Mississippi River. This began some 2800 years ago with the de­
velopment of the St. Bernard and subsequent deltas toward the east and
southeast. The deltas were areas of rapid deposition and they buried
the Pleistocene shelf beneath greater thicknesses of sediment. As the
deltas advanced seaward, however, the trunk stream began to scour deeply
into the underlying Pleistocene deposits, so that the bed of the present
channel and a large portion of its banks consist of Pleistocene deposits.
This is the condition from river mile 157 at College Point to about 25
miles south of New Orleans. The width of this entrenchment is controlled
by the amount of river migration, which nowhere exceeds three or four
miles. The trench is too narrow to be shown in fig. 5. In plates 3-7,
its width is indicated by the lateral extent of point bar deposits.
Shallow Pleistocene contours on these plates are terminated wherever they touch the river or flanking point bar deposits. Contours greater than average depth of river scour, i.e. -150 ft msl, are extended across the point bar areas.

The existence of the Pleistocene in the bed and portions of the bank of the river has a significant effect on river migration. The ratio of river distance to airline distance between Baton Rouge and College Point, for example, is 2:1. The ratio of river distance to airline distance between College Point and New Orleans is only 1.3:1. It is true that this river-airline distance ratio is even smaller downstream from New Orleans where the Pleistocene lies at a depth too great to form the river bed. However the straightness of the river channel south of New Orleans is attributed to its youth and to the fact that here the bed and banks of the river consist of cohesive prodelta clays almost as nonerodible as the Pleistocene. See Chapter VI for further discussion of this topic.

The importance of the Pleistocene in foundation design is self-evident. The deltaic plain soils overlying this horizon are for the most part of low strength. Many of the heavier structures are founded on piles reaching the Pleistocene. Some piles extend well into the Pleistocene materials and a knowledge of the type and lateral distribution of soils, and the distribution of strengths in the Pleistocene is essential. Recognizing and establishing the elevation of this horizon in the subsurface are important in any foundation investigation in the deltaic plain.

Previous studies point out the following criteria as aids to distinguishing the Pleistocene in boring returns: (a) Color of the
sample typically changes from dark gray, blue gray or black to an oxidized, mottled yellow or tan. In some cases the color change is to light greenish gray. (b) There is usually a marked decrease in water content. (c) There is a distinctive stiffening of soil consistency and a decrease in rate of penetration of sampling devices, an indication of increase in soil strength. (d) Calcareous concretions are typical.

These distinguishing characteristics are generally in accord with the data on logs of borings examined in the present study. Areas where a determination of the Recent-Pleistocene contact is sometimes difficult include embayments or estuaries in the old Pleistocene surface during the time of lowered sea level, where the present Mississippi River has scoured deeply into the Pleistocene surface, and where this surface is deeper than -150 ft msl. Many re-entrants or embayments in the Pleistocene surface must have acted as estuaries for considerable periods of time while sea level was at its lowest stand or while it was rising. The result was that little oxidation of the contact took place. Where oxidation did take place, oxidized strata may have been removed by further entrenchment of the estuary.

A similar situation occurs where the present river and its abandoned courses have cut channels into shallow Pleistocene deposits. The upper thoroughly oxidized zones in such instances are often entirely removed by fluvial scour and, except for a slightly greenish cast and usually--but not always--a higher strength, the material may be hard to distinguish from Recent deposits. Any time the Pleistocene is at a depth greater than 200 ft, the boundary between Recent and Pleistocene deposits may be difficult to establish.

The depth of oxidation of the Pleistocene deposit varies
considerably. Oxidation is deepest where the Pleistocene is very close to the surface; mottled tan or yellow colors are found to depths of 50 ft or more in the Pleistocene. Boring MS-8, in Section H, plate 17, illustrates this. This boring encounters Pleistocene at 0 ft msl. Tan oxidized colors are found to -55 ft msl. Partially oxidized material with greenish-gray colors, and gray unoxidized material are found to -115 ft msl. Tan colors begin again at -115 and extend to -145 ft msl; greenish-gray colors are found to -170 ft msl; and gray unoxidized material to -188 ft msl, the bottom of the boring. This boring is fairly typical of Pleistocene materials. Very stiff to stiff consistencies are characteristic of the oxidized or partially oxidized Pleistocene; stiff to soft consistencies are typical of the unoxidized gray Pleistocene.

This correlation of consistencies and strengths with oxidation is expectable. The reasons for the erratic distribution of the zones of oxidation are only partially understood, and the phenomenon occurs in nearly all borings penetrating the Pleistocene in the study area. As the depth at which Pleistocene is encountered in a boring becomes greater, the thickness of the upper, oxidized zone decreases. Where the Pleistocene is found at depths below -100 ft msl, tan colors are often lacking entirely and greenish-gray colors predominate. Where the Pleistocene is deeper than -150 ft msl, both tan and greenish-gray colors may be absent at the Recent-Pleistocene contact. Here variations in consistency, cohesive strength, water content, and the occurrence of concretions become important diagnostic characteristics.

The great thickness of oxidation where the Pleistocene occurs at
shallow depths is understandable. It probably reflects the greater depth to water table in such areas during the time of lowered sea level and the much longer time they were subaerially exposed and subjected to oxidation. There is also reason to believe that where the Pleistocene occurs at depths of less than -50 ft msl it was never subjected to the marine erosion accompanying rising sea level during waning glaciation, the shallow surface having subsided and been covered with a protective blanket of deltaic deposits. Where the Pleistocene occurs at greater depths much of the oxidized part of this surface was probably removed by wave action. Differential depths of marine erosion may account for the fact that tan oxidized deposits sometimes mark the contact between Recent and Pleistocene deposits even where it occurs at depths as great as 400 ft. In other instances tan deposits are absent when this horizon is found at depths as shallow as 150 ft.

Why oxidized zones occur at great depth in the Pleistocene, as is the case in MS-8, is unexplained. Erratically spaced oxidized Pleistocene strata are found sandwiched in with unoxidized Pleistocene strata in almost all of the borings which penetrate very deeply into the material. In the borings shown in plates 11-44, there is a slight indication that a second zone of oxidation may occur—as it does in boring MS-8 (plate 17)—at about -100 msl. This is the grossest sort of generalization, however. There also is some slight tendency for the deeper oxidized zones to be more prevalent in the coarser grained materials. It is possible that the Pleistocene was once uniformly oxidized to great depths, and that the erratic distribution of oxidized zones is the result of selective chemical reduction of certain strata. It is also possible that erratically disposed oxidized zones are buried Pleistocene natural levees or similar environments
that were oxidized at the time of deposition.

Regardless of the causes of this phenomenon, the engineer should be aware that relatively soft, unoxidized zones that may be important in foundation design do occur in the Pleistocene.

It should be remembered that the Pleistocene is considered to be an ancient alluvial-deltaic plain of an ancestral Mississippi River, and that the lateral and vertical distribution of soil types of which it is comprised are just as complexly interfingered as those of the Recent deposits. The occurrence of shells in samples taken from the Pleistocene beneath southeast Louisiana suggests that the present deltaic plain overlies an ancient Pleistocene deltaic plain with similar environments of deposition and similar associated soil types. Data are far too scarce to attempt to reconstruct the paleogeography of this ancient deltaic plain; however, it undoubtedly contained thick wedges of prodelta clays, buried sand beaches, bay-sound deposits, and other environments characteristic of the present deltaic plain. Ancient rivers probably meandered across its surface and left behind abandoned courses flanked by point bar deposits. The purpose of recreating this hypothetical situation is to emphasize the fallacy of correlating soil types between widely spaced borings in the Pleistocene. As in the case of the Recent deltaic plain deposits, widespread correlation would be very misleading without identifying the environment of deposition in which the Pleistocene material has been laid down.

**Fluvial Environments**

Fluvial environments of deposition flanking the Mississippi River from Donaldsonville to the Gulf consist of natural levee, point bar, abandoned distributary, abandoned course, backswamp, and substratum deposits. Because of the configuration of the Pleistocene surface in
the study area as discussed in the preceding paragraphs, the backswamp and substratum environments are found only as far downstream as river mile 157 at College Point. It will be recalled that it is here the present Mississippi River leaves the major valley entrenched in the Pleistocene and trends east-southeasterly across a shallow, relatively uneroded Pleistocene shelf. Downstream from this point sediments can be subdivided into those characteristic of the deltaic plain; upstream, sediments are generally divisible into those characteristic of the alluvial plain.

**Backswamp**

The use of the term "backswamp" is decreasingly appropriate downstream from Baton Rouge. A thick fine-grained topstratum, comparable to the backswamp upstream from Baton Rouge, overlies a sand and gravel substratum; however, as far upstream as Baton Rouge occasional layers of shell are found in boring sampling this unit, suggesting that the area was covered in fairly recent times by waters of shallow bays or sounds. Occasional sandy units also occur that suggest an intermingling of backswamp and deltaic plain environments of deposition far more complex than the simple build-up of backswamp clays in floodplain depressions. This is even more pronounced in that part of the study area between Donaldsonville and College Point. Here a fine-grained topstratum overlies a well-defined substratum, but shell layers and coarse-grained strata are frequently intercalated with more characteristic fat clays. The term "backswamp" is used in subsurface sections in this area (plates 11-18), but with reservations. Downstream from College Point the term is entirely inappropriate.
Substratum

Although the concept of a substratum of fluvial sand, or sand and gravel, underlying a fine-grained topstratum is basic to understanding the stratigraphy of the Recent deposits in most of the Mississippi Alluvial Valley, it introduces complications in the area under investigation. In the latitude of Donaldsonville substratum sands are found only below an elevation of about -100 ft msl. From College Point (river mile 157) to well south of New Orleans, the ancient Pleistocene surface often lies at depths of less than 100 ft. Substratum sands, therefore, were not deposited on this shallow shelf. South of New Orleans the Pleistocene is encountered at progressively greater depths, reaching a depth of about 600 ft at Head-of-Passes. But here, too, the concept of a flu­vially deposited, coarse-grained substratum is inappropriate since mate­rials lying directly above the Pleistocene were deposited for the most part in a marine environment.

Consider contours on the Pleistocene surface in fig. 5. Note that the deepest part of the Mississippi River entrenchment trends south­eastward about 15 miles west of Houma, Louisiana. Substratum sands fill this trench, and the top of the sands occurs at progressively greater depths in a downvalley direction. The top of the unit is also believed to be at progressively greater depths to the east and west of the axis of entrenchment. Coarse materials deposited in a braided stream envi­ronment in the substratum should be concentrated along the axis of greatest entrenchment. Coarse materials carried east and west of this axis were enveloped and incorporated with the marine environments asso­ciated with a rising sea level.

In keeping with this, note that Section I (plate 18), which crosses the river at College Point, is the farthest downstream of the sections
on which the term substratum is used. In the areas bordering the river downstream from this point the term is not applicable.

Borings encountering the substratum between Donaldsonville and College Point show it to consist predominantly of poorly graded fine sand. Fig. 6 summarizes data on borings encountering the substratum in this area. The data are assembled in 20-ft increments of depth. Notice the high incidence of poorly graded fine sand (SP) between elevations of -100 and -140 msl. Although gravel content increases appreciably with depth, the substratum is markedly finer grained than the substratum at comparable depths at, say, Old River near the Louisiana-Mississippi border. Fig. 6 also shows estimated ranges of permeabilities for each 20-ft increment of substratum. These ranges are based largely on experience with materials of comparable grain size in other portions of
the Lower Mississippi Valley. Notice the reasonably high permeabilities in the lower portion of the substratum despite the persistence of fine-grained sand. The high permeability of these sands is generally corroborated by wells pumping from substratum deposits in the Donaldsonville area where yields of from 1400 to 2100 gpm have been measured with specific capacities averaging more than 40 gpm per foot of drawdown.

The most prevalent conception of the nature of the wedge of coarse-grained sediments in the substratum is that it consists of an uninterrupted sequence of progressively coarser materials with depth. If Broecker's and Curray's interpretation of events, discussed in Chapter III, is accepted, this should be the case. If McFarlan is correct in assuming a long—at least 18,000-year—stillstand of sea level, there should be a reasonably well-marked change in the nature of the substratum deposits at about -250 ft msl or at a somewhat greater depth consistent with regional subsidence since that time. A fine-grained topstratum should have been preserved in some instances and sand density should increase markedly below this horizon.

Fig. 7 shows grain-size distribution curves from 5 samples from the substratum encountered in boring MS-4 (Section A, plate 3). Note the poor gradation of the fine sand samples at -109 and -129 ft. Note also the skip-grading in the sand and gravel units at depths of -149, -169, and -179 ft. Coarse to medium sand sizes are curiously lacking, a characteristic found in the majority of the samples available from the substratum in the study area. Whether this material consists of finely stratified layers of poorly graded fine sand between layers of poorly graded gravel, or of fine sand intermixed with the gravel is unknown. In the former case, permeability should be high. In the latter case
Fig. 7. Grain-size distribution of samples taken from the substratum in boring MS-4 (see plate 3 for graphic log of boring)

the permeabilities may be much lower than indicated in fig. 6. Based on the effective grain size (D_{10}) of the sand-and-gravel units, for example, a permeability of only $500-600 \times 10^{-4}$ cm/sec should be expected.\(^{51}\)

The curious lack of medium and coarse sand sizes has been observed in many fluviatile sediments. Udden,\(^{45}\) Wentworth,\(^{56}\) Einstein, Anderson and Johnson,\(^{11}\) Hough,\(^{23}\) Pettijohn,\(^{34}\) and Sundborg\(^{40}\) have observed this fact and attempted to explain it. Some suggest that the process of weathering of the source rock and the process of wear during transport produce a sediment where certain grain sizes are more common than others, mainly because certain grain sizes, among them the medium and coarse sand sizes, are mechanically unstable. Sundborg suggests that the reason lies in the selective transportation of material by flowing water. He bases his conclusions on work by Shields\(^{39}\) who postulated that "the ratio of the force exerted by flowing water along the bottom to the
resistance of a layer of sand grains is a function of the ratio of the grain size to the thickness of a laminar sublayer." Based on this theoretical approach and some laboratory experimentation Sundborg concludes that "when gravel grains have been worn down to a size of about 5-6 mm, the transportation of them by the stream becomes more relentless, and they are often prevented from coming to permanent rest until they have been worn down to a size of 1-2 mm or less. This may well be an important cause of the general deficiency of particles in the interval 1-6 mm."

It is possible that the lack of coarse and medium sand sizes in the substratum substantiates Sundborg's views; that the substratum was laid down by braided streams which permitted finer and coarser materials to remain behind, but selectively sorted the intermediate sizes for deposition farther downvalley. If this is true, there should be a concentration of medium and coarse sand sizes in the more southerly areas of the entrenched valley, in those areas where this particle size eventually reached the then-lower sea level. This hypothesis is obviously not valid on today's Lower Mississippi. Coarse and medium sand sizes are found in only insignificant quantities in the point bar deposits which flank the channel in the study area and are essentially absent in the delta. It is inconceivable that such sizes could be worn by attrition to fine sand sizes in the 180 miles of river transport between Donaldsonville and the Gulf. The lack of such sizes must therefore be attributed to the very small quantities of such sand sizes that reach this lower portion of the river. The reasons for the lack of gravel sizes in the Lower Mississippi have been discussed elsewhere. Apparently the process of selective sorting and deposition so effective
in eliminating gravel sizes in the lower river has also winnowed out the larger portion of the coarse and medium sand sizes. It would be interesting to study the occurrence of coarse and medium sand sizes in point bar deposits successively farther upstream from Donaldsonville and to contrast this with the occurrence of similar sizes in bed material samples. A knowledge of the prevalence of skip-grading, which involves a lack of coarse and medium sand sizes in the substratum, might also prove of considerable value in the study of sediment transport problems.

**Point bar**

One of the most abrupt and significant of the changes in soil type along the river in the study area is that between the silts and sands of the point bar and the older deposits which border and underlie them. They flank the present river or abandoned courses of the river, and normally occur on the insides of bends to which the sandy deposits accrete as the bends grow. Recognition of point bar deposits is therefore relatively simple where boring logs are available, even though natural levee deposits often effectively mask the arcuate markings which help to identify them on aerial photographs in the central and northern portions of the valley. Most of the borings made expressly for this study were located to help identify these deposits and to delineate their extent.

A tabulation of more than 2000 samples from point bar deposits between Donaldsonville and the Gulf indicates that close to 50 per cent consist of poorly graded fine sand. Fig. 8 shows grain-size curves of materials at various depths within the typical point bar, the characteristic increase in grain size with depth, and the percentage of soil
Fig. 8. Percentage of soil types in point-bar deposits in study area and grain-size distribution of typical deposit.
types normally found within the point bar deposits along the lower 190 miles of river.

Other than this characteristic increase in grain size in a given point bar with depth, there are few unifying generalizations that can be made. Examination of the borings available in the study area shows no decrease in sand with distance downstream, for example, or increase in clays. Depths to sand are highly variable, and soil types change rapidly both horizontally and vertically. An important point to consider in interpreting borings made in point bar deposits is that lateral correlation based on borings spaced at distances greater than 200 ft is not recommended. For this reason subdivision of the finer-grained upper portions of the point bar is not attempted on most of the subsurface sections accompanying this report. An exception is in the basal one-third to one-half of the point bar deposit where experience has shown that a fairly clean, fine-grained, homogeneous sand can be expected.

The nature of the coarser deposits in the point bar is illustrated in fig. 9. The photographs are of samples taken from a 6-in. continuously cored boring made just downstream from New Orleans. Note the intricate small-scale stratification characteristic of the SM-type soils, i.e., samples 12-B and 14-B. This stratification is apparently the result of the arrangement of the deposits in alternating, paper-thin layers of silt and fine sand. Mixing these layers in the laboratory results in the classification of the material as an SM soil. Cross-bedding, thin laminations, and thin, dark, organic strata are common. The photograph of sample 12-B shows some of the thin layers of granular organic fragments. Such very thin organic layers and fine flecks of organic matter are found disseminated throughout the point bar deposits;
Fig. 9. Details of stratification in point-bar deposits sampled in boring MS-32A at English Turn
however, segregation of peat in any considerable quantity is not considered either typical or significant. Occasional peat reported from some of the point bar borings (see plates 13 and 17) are probably pieces of rotting wood or water-worn organic pellets that are of such limited areal extent they are considered of little consequence in affecting consolidation or strength characteristics of the material.

Sample 14-B shows remarkably warped strata sandwiched between essentially level strata. This probably resulted from folding of the strata after deposition, possibly at the time of deposition of the strata that overlie the warped sequence. Sample 22-A illustrates the massive bedding characteristics of the thick section of poorly graded fine sand typical of the basal portions of the point bar deposit. Only at the very bottom of the point bar deposits, in sample 30-C, is there a reoccurrence of noticeably thin stratification. Shells found in this sample suggest that this may be a transitional environment. The effective grain size, $D_{10}$, of the basal sand section ranges between 0.80 and 0.18 mm. Horizontal permeabilities should range between 100 and 800 cm/sec $\times 10^{-4}$. *

In the bend just upstream from Donaldsonville (plate 3) and in the Laplace area (plate 5) a very silty sequence of deposits has been tentatively identified as point bar deposits, and is shown with a different symbol than the rest of the point bar materials in the study area. These materials are notably finer than the normal sandy point bar deposits, consisting of inappreciable amounts of sand and more than 75 per cent silt. Arcuate markings characteristic of point bar deposits

*Based on an extension of the curve shown in fig. 17 of reference 51.
help to identify these areas on aerial photographs. At Geismar these markings are particularly well preserved. The Carville quadrangle, a portion of which is shown in fig. 10, shows many of these trends as curved lowlands on the floodplain surface. Note particularly the curvature of the swampy lows at Southwood, the one followed by New River (identified in plate 3, but not in fig. 10), and the series trending northeast just downstream from Geismar. The direction and curvature of these markings conform very poorly with the curvature and size of the present Mississippi. The stream which made them may have been an appreciably narrower stream with a considerably tighter meander loop. In all probability the silts which are found in these areas were left by a small stream such as the Yazoo which is believed to have once entered the Gulf at this point at the time when the Mississippi occupied its Teche course on the other side of the alluvial valley (fig. 3). It may also represent an early distributary of the Mississippi—a stream which was eventually enlarged to the size of the present Mississippi. The remnants of deposits left by such a stream should occasionally be preserved along or closely adjacent to the present river, and undetected remnants probably occur as far downstream as New Orleans.

Natural levees

The height, thickness, and width of the natural levees flanking the Mississippi River decrease constantly between Donaldsonville and the Gulf. Similarly, the grain size of the material comprising the levee generally decreases in a downstream direction. Fig. 11 is a schematic representation of typical height, width, thickness, and soil type from river mile 186 to 20 above Head-of-Passes. Borings selected
Fig. 10. Distribution of silty and sandy point-bar deposits near Philadelphia Point upstream from Donaldsonville, La.
for this diagram were chosen wherever possible from near the crest of the natural levee where the coarsest materials are normally found. The levee decreases rapidly in elevation and thickness and generally decreases in grain size with distance landward from the crest. This diagram does not attempt to show the actual distribution of soil types in 166 miles of natural levee, but rather the change in the percentage of each soil type with distance downstream. The boring at mile 186 on the left side of the diagram, for example, began at an elevation of 28 ft msl, encountered randomly distributed soil types of which 50 per cent were CL, 25 per cent were ML, and 25 per cent were SM. The thickness of the natural levee deposit in this instance was 19 ft. The boring at mile 20, on the other hand, began at 4 ft msl, penetrated 12 ft of natural levee deposit, and samples consisted entirely of CH.

The width of the natural levee varies between 4 and 2-1/2 miles
between Donaldsonville and New Orleans and narrows perceptibly south of the city, an indication of the youth of the channel south of New Orleans. It is interesting to speculate on the future of the natural levee in those extreme lower reaches of the river protected by artificial levees. Protected from overbank flow during high-water periods by the artificial levees, the natural levees have ceased to grow. Normal subsidence of the area because of consolidation of the soft deltaic plain deposits has been augmented by the weight of the artificial levees. Natural levee widths in these lower regions of the river are becoming less, and unless fill materials are brought in to build up these gradually subsiding areas, saline to brackish water marsh will eventually cover the natural levee areas landside of the artificial levees. For example, the natural levee has almost completely disappeared just upstream from Potash (see plate 9, mile 41). Contrast the width of the natural levee in the unprotected Pointe à la Hache Relief Outlet on the other side of the river.

The size of the natural levee upstream from New Orleans has probably remained essentially the same for many hundreds of years. Increase in height results chiefly from gradual extension of the mouth of the stream seaward, and since the distance from Donaldsonville to the distal ends of the St. Bernard delta was somewhat comparable to the present distance from Donaldsonville to the Gulf, it is doubtful if the height of these levees has increased appreciably since the abandonment of the St. Bernard delta. Crevasses increased the size of the natural levee locally. Before the construction of the artificial levees, however, these crevasses were probably more frequent but less spectacular than crevasses since that time. Notable local extensions of the natural levee accompanied the crevasses of historic time. Location and dates
of many historic crevasses are shown in plates 3-10 and fig. 1. One of the more spectacular results of crevassing through artificial levees was the creation of deep scour pools immediately landside of the crevasse. Depressions still mark many of these scour pools. Little is known concerning the type of material with which they are filled.

The strength of natural levee deposits is high. The characteristic range of strength of the cohesive soils is between 800 and 1200 lb/sq ft based on unconfined compression tests. Desiccation and oxidation of these materials after deposition undoubtedly account for this high strength. Of interest, in this connection, are buried natural levees, occasionally located by borings, which retain considerable strength even though now submerged beneath the water table. Such buried natural levee horizons are probably most common in that part of the study area upstream from Laplace, since most are thought to be correlative with the ancient Maringouin system of the Mississippi which occupied this area many years before the formation of the present river channel and the St. Bernard and subsequent deltas (fig. 3). Saucier has identified one such buried natural levee in the vicinity of Reserve (see Section L, plate 2l). Very carefully logged borings made in this area have identified two well-developed natural levee systems flanking the Mississippi. The landward ends of these levees are separated by an organic swamp or marsh deposit. Riverward, the two natural levees lie on top of one another and reach a maximum thickness of 35 ft. An interesting feature is that each has an upper oxidized zone and a lower unoxidized zone. Whether the lower zones were never oxidized, or whether they were oxidized and later chemically reduced is unknown. Unfortunately, no data are available concerning comparative strengths of the two natural
levee systems. Field determination of consistencies indicates a roughly comparable strength for the oxidized portions of both levees.

Abandoned courses and distributaries

The development and abandonment of courses and distributaries in the study area are essential parts of the geologic history of the deltaic plain (Chapter III). Known and many inferred positions of such features are shown in plates 3-10 and fig. 3. Abandoned courses are few in number and are large enough to have left markings fairly easily distinguishable on the floodplain surface. Abandoned distributaries are much more difficult to recognize and delineate, but they are often of considerable importance in foundation problems. They tend to cut haphazardly across other deltaic plain environments of deposition where soils are fairly homogeneous, and when abandoned they leave behind narrow ribbons of sediment ranging from 50 to 500 ft in width and from 10 to 100 ft in depth. Discontinuities such as these in otherwise homogeneous strata are often difficult to locate on aerial photographs, and unless a boring happens to be located in such a deposit, may be entirely missed in foundation explorations.

Unfortunately, abandoned distributaries are most difficult to recognize where their recognition is most important—in areas close to the present river. Here they are invariably covered and completely masked by natural levee deposits. Experience has shown that the most successful method for locating these features on air photos is to begin by carefully studying the marsh or swamp areas and to work toward the river. The abandoned distributary can usually be traced with some degree of success in the marsh, and although it will be completely masked within two or three miles of the river, the trend of the
abandoned feature can easily be estimated. Fortunately, meanders are relatively rare in distributaries, and once a trend has been established in the marsh this trend can be extended along a fairly straight or gently arcuate path where it is masked by overlying natural levee sediments.

The size or importance of the deposits filling an abandoned distributary is difficult to ascertain on aerial photographs. Small, recently abandoned distributaries often are better marked than large, significant distributaries abandoned for some time. The considerably larger number of distributaries mapped downstream from New Orleans (plates 7-10) than upstream is partially a reflection of this. Only three abandoned distributaries are shown in plates 3-5. The farthest upstream is north of Laplace in plate 5. This distributary once trended northward between Lake Maurepas and Lake Pontchartrain and is undoubtedly the cause of the slightly higher land which separates these two water bodies. Faint markings of a system of distributaries presumably associated with the ancient Maringouin course of the Mississippi are mapped in the southeast corner of plate 5 and continued eastward in plate 6. The position, and even the existence of this system of distributaries are controversial. The third abandoned distributary system mapped upstream from New Orleans is the well-marked Bayou Metairie which trends northeasterly through New Orleans.

There are undoubtedly more abandoned distributaries in the area covered by plates 3-6 than are shown; however, it is believed that these features are not as common in this portion of the river as they are downstream from New Orleans. In all probability the gradually subsiding Pleistocene shelf was well covered with sediments long before the advent
of the Mississippi River and its distributary systems some 2800 years ago. Carbon-14 dating of marine sediments overlying the Pleistocene shelf indicates dates in excess of 10,000 years. It is quite probable that except for the earliest deltaic distributary system left by the Mississippi-Maringouin course, very few distributaries existed upstream from New Orleans; it is also probable that the St. Bernard established its earliest course over a marshy land area and did not begin to bifurcate into a significant distributary system until it reached open water along its eastward trend in the vicinity of New Orleans. Distributaries were apparently directed predominantly eastward and southward in the New Orleans area, and northward upstream from New Orleans.

The soils which fill abandoned courses and distributaries are closely related to the history of development and decline of these features. Although these processes are far from thoroughly understood, a reasonable hypothesis is presented in reference 47. Indications are that the abandonment of a Mississippi River course is a gradual process until a critical stage in the diversion process is reached. This critical stage usually occurs when 30 to 40 per cent of the master stream's flow is being diverted through the diversion arm. Following this critical stage there appears to be a rapid deceleration of the diversion process during which the former full-flow course is plugged with sand just downstream from the point of diversion and the new channel rapidly enlarges to take the entire flow. After abandonment of the former course, only high water or flood flow is capable of breaching the sandy wedge which forms at the head of the abandoned course. Sandy materials are distributed for some distance downstream from this point by these flows, but most of the abandoned course receives only the
finest materials which are carried in suspension.

For most of its length and for a considerable time after abandon-
ment, the course is a fairly deep elongate water body which gradually
fills with fine-grained sediments carried in by flood flow in much the
same way that the shorter segments of the stream isolated as chute or
neck cutoffs are filled. If this were the only source of material the
resulting body of sediment would consist of a wedge of sand, gradually
thinning downstream, overlain by a complementary clay wedge thinning
upstream. However, indications are that in the deltaic plain this
sequence is complicated by the introduction of both clays and sand
carried upstream and deposited in the abandoned course by tidal
currents.53

Data are too sparse at present to determine the effects of these
currents on the seaward portions of the filling course, but available
boring data on the abandoned St. Bernard course52 indicate that a sandy
wedge may develop upstream from the seaward extremities of the abandoned
course in much the same way as one develops downstream from the course's
landward extremity or its point of diversion from the main stream. On
being abandoned, the course channel would be considerably deeper up-
stream from this shoal, and tidal currents would probably continue to
deposit sands at the shoal and carry fine sediments into the upstream
pool, thus duplicating the situation at the upstream extremity of the
course. The central portions of the abandoned course, according to
this hypothesis, would be the site of maximum clay and silt deposition.

Even though present knowledge of the sediments filling abandoned
courses is meager, there is every indication that the ribbons of
abandoned course deposits in the study area afford some of the firmest
foundation materials at comparatively shallow depth in the region. There is usually an upper zone of low-strength material with high water content and fairly high organic content which may range from 20 to 40 ft in thickness depending on the distance of the deposit from the original point of diversion. Below this zone, high strength sand and silty sand are the most common soil types, and may reach thicknesses of from 50 to 100 ft. Organic content in this lower zone is negligible. This is true of the Lafourche course, the St. Bernard course, and the Barataria course. The abandoned course of the Maringouin-Mississippi shown in plates 5 and 6 (if it exists) may contain a much greater thickness of compressible silts and clays.

The processes involved in distributary development have been explored by several investigators. Welder made an extensive study of the development of the Cubit's Gap system of distributaries in the present delta; these distributaries were formed by the crevassing—in this instance the artificially induced crevassing—of the low natural levee near Head-of-Passes. He and others have considered the typical development of distributaries as load is deposited at the mouths of individual channels where they enter the sea. A sandy shoal is formed, around which the channel bifurcates. Each channel then continues its own development and splits in turn to form new distributaries. The result is a network of channels which distribute the water of the main channel through a series of minor channels to the sea. The intricacy of this network ranges from many distributaries, the so-called "horse-tail" delta left by the Lafourche-Mississippi course, through less intricate systems such as those formed by the St. Bernard, to the present "bird's-foot" type of delta distributary system with only a few
distributaries presently operative at Head-of-Passes. Indications are that the intricacy of the distributary pattern can be correlated with the depth of water in which the distributary system advances. Where the water body into which the delta is built is shallow, many deep narrow distributaries are typical. Where the original depth of water is deep and the distributaries must form entirely within the coarser materials forming the bars at their mouths, fewer, wider distributaries are developed.

The process of abandonment of a distributary is believed to parallel closely that of the abandonment of a course. Wedges of sand are built at the point where the distributary leaves the main course. These extend for variable distances downstream. In the sizeable Metairie distributary of the Mississippi that trends through New Orleans (plate 6), the few borings available indicate a sand wedge filling the bottom of the abandoned distributary that extends downstream for a distance of about 9 miles. Overlying this sand wedge is a complementary wedge of fine-grained material. A sand wedge of such size may not develop in any but the largest of distributaries; however, deep, narrow, sand-filled distributaries are known to exist in the abandoned Lafourche delta. Welder tested materials filling a minor abandoned distributary in the deltaic complex south of Main Pass at Head-of-Passes (plate 10). He found a clay fill underlain by a distinctive wedge of silty clay and clay silt. Borings that penetrated a considerable section of organic clays and peats were interpreted as representative of abandoned distributary fill. Present indications are that materials forming the distributary fill are highly variable, but a wedge of relatively coarse material, compared to the remainder of the
distributary fill, always plugs the upstream end.

**Fluvial-Marine Environments**

The sequence of fluvial-marine deposition results in a complexly interstratified deposit which, nevertheless, can be divided into distinctive lithologic entities. Preceding each deltaic advance into a water body is a wave of fine-grained deposition swept seaward by the stream and redistributed by longshore and tidal currents. These are the prodelta deposits—clays at some distance from the mouths of the deltas and silty clays near the delta front. As the delta advances, each distributary is built seaward on a bed of the coarsest material carried by the stream—in the case of the Mississippi, fine-grained sand. The coarser sediment settles near the mouths of the distributaries as subaqueous bars, and along their margins first as subaqueous, then above-water natural levees. Land surfaces form as the sediments build up to and above the level of the sea. This is the intradelta environment. As distributaries continue to extend themselves seaward, well-defined lowlands develop between them. Into these areas only the fine-grained deposits are carried by distributary overflow, wind, or tidal currents. So that within, or more normally overlying the intradelta coarser materials are discrete, wedge-shaped bodies of interdistributary clays.

The three fluvial-marine environments of deposition, the prodelta, the interdistributary, and the intradelta, make up an estimated 75 percent of the Recent deposits of the deltaic plain. In effect, all the sediment carried to the sea as suspended load by the Mississippi River is deposited in one of these environments. Estimates of the amount of
sediment carried to the Gulf by the Mississippi vary, but 400 to 500 million tons annually is generally accepted as the right order of magnitude.

**Prodelta**

Prodelta deposits are the first of the terrigenous sediments introduced into a depositional area by an advancing delta. Although widely distributed by wind, marine, and fluvial currents, there is a gradation of prodelta silty clays into prodelta clays with distance from the mouths of active distributaries. In profile this depositional sequence is manifested by a normal gradation upward in the prodelta clay sequence from fine to coarse, in this instance from the finest clays to silty, and rarely, sandy clays.

Prodelta deposits are distributed in plan as a relatively uninterupted stratum beneath the shallow water of offshore southeastern Louisiana. Lenses of this environment extend inland beneath the land areas, but greatest thicknesses occur in the offshore areas. The thickness varies generally with the depth to Pleistocene; the greater the depth to this ancient sedimentary horizon, the greater the thickness of prodelta deposits. The thickness of the prodelta materials along the river in the study area increases progressively downstream. Likewise, the depth to the top of these clays and silty clays increases progressively downstream. Fig. 12 shows the depth at which the top and the base of the prodelta clays can be expected to occur between New Orleans and 20 miles above Head-of-Passes. Note that the thickness of the unit increases from about 40 ft at New Orleans to more than 120 ft at river mile 20. In this lower section of the river a large proportion of the bed and banks of the channel consists of fat, cohesive, prodelta clays.
Fig. 12. Thickness of prodelta clays and the relation of these deposits to river depth south of New Orleans.

as is indicated by the thalweg of the river superimposed in fig. 12.

The predominant soil type associated with the prodelta environment is fat clay (CH). Studies of more than 1000 samples from this environment show it to consist of 96 per cent fat clays. A further subdivision, based on an adaption of the Unified Soil Classification System to fine-grained soils (see plate 2 and the discussion at the beginning of this chapter), indicates that 79 per cent of prodelta deposits consists of the finest of the fat clays, the CH₄ classification. Natural water contents of these materials range from 30 to 90 per cent dry weight, and their unit weight ranges from 92 to 118 lb per cu ft. Cohesive strengths of the prodelta clays are relatively high, the characteristic strength is between 200 and 700 lb per sq ft. Cohesive strengths
greater than 1000 lb per sq ft are not uncommon. Cohesive strengths characteristically increase with depth.

**Intradelta**

Intradelta deposits are, in essence, the coarse deposits associated with delta advance. At the mouth of a distributary the velocity of its water is checked and the greater part of its load is deposited as distributary mouth bars. Sediments accumulate on the bar crest or are distributed as submerged fans on the seaward sides of the bars. As the distributary is built seaward, it may cut a channel into these coarse materials or the channel may split around the bar. The process is then repeated in each of the smaller channels. Usually one of these distributary channels is abandoned after a time, and the remaining channel enlarges. Distributary channels are initiated not only by bifurcation around bars, but by crevassing in areas close to sea level where natural levees and stage differences are low. These distributaries deposit coarse material into what may have been quiet waters in which only clays had previously been deposited. Thus, the coarse materials that are preserved as part of the deltaic plain as a delta builds itself seaward are complexly interfingered with clays that settle out in the quiet areas between distributaries.

Even the smallest distributary is preceded by waves of coarse intradelta materials; conversely, every area between myriad individual distributaries is a potential trap for interdistributary clays. Consider also that where a particular distributary eventually becomes the main course, a sizeable wedge of natural levee deposits irregularly and often imperceptibly grades downward into intradelta deposits. Borings made in the present Mississippi River delta found reasonably
distinct bodies of coarse intradelta, and fine interdistributary materials, the former associated with the major passes, the later lying between them. The sandy deposits associated with each major distributary are appropriately termed "bar fingers" because they project as definite fingers of sand or sandy silt beneath and immediately to the flanks of these distributaries. The present bird's-foot delta has only a few major distributaries. However, ancient deltas of the Mississippi have had much more numerous and complexly disposed distributaries, the number and complexity appearing to be inversely proportional to the depth of marine waters into which the deltas were built. As mentioned earlier, the Lafourche delta (fig. 3) has been called a horsetail delta because of its myriad distributaries. Major distributaries were so closely spaced that intradelta deposits form a fairly continuous sandy sequence without intervening clays. Fisk has termed these features "sand sheets."

An intermediate situation is represented by the somewhat less complex distributary system of the St. Bernard delta. Here division of the intradelta from the interdistributary clays is difficult, but a fairly reliable division of the coarse deltaic from the fine deltaic material is possible. A recent study of soil conditions along possible routes of the proposed navigation channel from New Orleans to the Gulf has permitted a fairly detailed reconstruction of the disposition of sediments in portions of the abandoned St. Bernard delta. In most instances, the position of the intradelta deposits in the subsurface was found to be marked on the surface by fairly well-defined abandoned distributaries. The coarse materials, as in the present delta, are disposed either in a triangular wedge having a flat base and the abandoned distributary at
its apex, or as a roughly diamond-shaped deposit that narrows at both the top and bottom in cross section. The most common variation to this general disposition of these deposits is the occurrence of the abandoned distributary along one or the other side of the triangular cross section rather than at its apex. This may be a reflection of bifurcation of the distributary around a bar, shifting the final distributary channel either to the left or to the right of the intradelta deposit.

A study\(^{53}\) of samples from the intradelta environment indicates that 75 per cent of the deposit consists of silt or coarser sizes. Sand particles are rarely larger than fine sand. Clay sampled in this study was interpreted as minor lentils of material more properly classifiable as interdistributary clays; however, delineation of such clay bodies normally requires an inordinate number of closely spaced borings which, except in very detailed soils investigations, would seldom be warranted. The alternative is to distinguish and delineate major coarse wedges of sediment that flank a course or a distributary, but to accept the fact that as much as 20 per cent of a given wedge may consist of thin, discontinuous clay units.

The distribution of coarse intradelta materials is of considerable importance in exploring engineering soil conditions. Since such materials can be expected to flank abandoned courses and distributaries, the positions of such abandoned features shown in plates 3-10 should be useful in predicting the occurrence of intradelta deposits in the study area. It should be remembered, however, that abandoned distributary deposits are not confined exclusively to narrow ribbons of sediment within the intradelta materials. Crevassing of main channels above ancient abandoned heads-of-passes permitted many distributaries to
develop, which cut channels into interdistributary clays for consider­able distances before they reached open water where they could build and begin to develop a course through their sand-silt intradelta deposits.

**Interdistributary**

Interdistributary sediments are those deposited in the low areas between active and abandoned distributaries of the past and present deltas of the Mississippi. The typical low-angle bifurcation of the distributary stream gives rise to trough deposits that "V" areally in an upstream direction and widen gulfward. The name "interdistributary" was first applied to the wedge of clay between the major passes of the present delta. Sid 47 Sediment-charged water spilling over subaqueous or low, subaerial natural levees leaves the coarsest sediment near the distributary as part of the intradelta or its natural levee sequence. The finest sediment settles out in the basins between distributaries. Clays discharged at the mouths of the distributaries may also be wafted inland by wave action and settle in these basins. Clays carried overbank by flood flows along the main channel upstream from its branching distributaries may also be deposited in the shallow brackish waters between the channel and either active or abandoned distributaries, and thus become part of the interdistributary sequence.

Considerable thicknesses of interdistributary clays may thus be deposited as the delta builds seaward. Recent studies indicate that about 90 per cent of the material in this environment consists of fat clays (CH). Interdistributary clays often grade downward into prodelta clays and upward into the richly organic clays of swamp or marsh deposits. The line of demarcation between the interdistributary and
overlying swamp and marsh clays is indistinct. True marsh or swamp begins when the watery area between distributaries or flanking the main channel has shallowed sufficiently to support vegetative growth. Where interdistributary clays overlie prodelta clays directly, a distinction based solely on visual examination of samples and the more elementary engineering characteristics is also sometimes difficult. Among distinguishing features are consistencies, associated soil strengths, and water contents. Consistencies in the interdistributary materials are usually logged as soft or very soft. Consistencies in the prodelta materials are characteristically medium to stiff. Water contents in the interdistributary materials are typically higher and strength decidedly lower. While prodelta materials are normally consolidated, with strength increasing consistently as depth and pressures increase, interdistributary clays are often underconsolidated. Cohesive strengths at depths as great as 200 ft are sometimes strikingly low, e.g., on the order of 300 lb/sq ft, and although strengths tend to increase with increasing depth, the trend is very erratic and inconsistent. It follows that the older the distributary system with which the interdistributary environment is associated, the more closely the clays approach normal consolidation. The most diagnostic of the criteria that can be used for determining the usually gradational contact between the interdistributary and prodelta environments is the occurrence of marine micro- and macrofauna in the latter. Although shells are sometimes associated with the interdistributary environment, they are rare and usually restricted to brackish water types.

**Paludal Environments**

The surface distribution of the paludal or swamp and marsh
environments which border the river in the study area is shown in plates 3-10. Marshes are flat expanses of grasses and sedges which occupy large areas adjacent to the natural levees, particularly downstream from New Orleans. Swamps are characterized by dense growths of trees and are most common in the lowlands flanking the natural levees in the upstream areas. The distinction between the two environments, it will be noted, is based primarily on vegetation. Distinction between subunits or types of swamp or marsh is also based on vegetation, and since vegetative type is very sensitive to the salinity of the water within which it grows, the names of marsh types mapped in plates 3-10 reflect the fresh, brackish, or saline nature of the surrounding water. There is some question as to the validity of such a classification for engineering soils purposes. However, increase in salinity is often associated with sedimentation or subsidence phenomena which have a decided effect on depositional characteristics. More data are needed to test the usefulness of this classification for engineering purposes.

The origin and physical characteristics of swamp and marsh environments in the deltaic plain of southeast Louisiana are comprehensively treated elsewhere. The discussion which follows summarizes what is known of the general lithologic characteristics of each of the paludal environments mapped in plates 3-10. The generalizations made are based on a number of soil profiles taken in each of the environments described; however, as stated above, much more data should be collected and analyzed before these generalizations are accepted.

**Fresh-water marsh**

This type marsh typically consists of a vegetative mat underlain predominantly by clays and organic clays. It occurs as a band along
the landward border of the marshlands and in areas subject to repeated inundation by fresh water. Fresh-water marsh occurs extensively near Head-of-Passes (plate 10) and the inland areas upstream from New Orleans. Typically, an upper, foot-thick mat of roots and other plant parts grades into a fairly soft organic clay which becomes firmer and less organic with depth. Peat layers are common but are generally discontinuous. Organic content generally varies from 20 to 50 per cent.

**Flotant**

Flotant, or floating marsh, occurs close to the right bank of the river near Head-of-Passes (plate 10) and near Poverty Point (plate 9). It consists of a vegetive mat underlain by watery, organic ooze. The soils sequence of a typical flotant area consists of a mat of roots or other partially decayed vegetative matter with some mixture of finely divided mucky materials from 5 to 15 in. thick. This is underlain by from 3 to 15 ft of finely divided muck or organic ooze grading to clay with depth. The ooze often consolidates with depth, and grades into a black organic clay or peat layer. Organic content of this type of marsh is typically high, usually greater than 50 per cent.

**Fresh- to brackish-water marsh**

This type of marsh, together with its saline to brackish counterpart, characteristically borders the natural levees of the river south of New Orleans. A typical soils sequence consists of, first, a mat of roots and other vegetative debris together with finely divided mucky materials from 4 to 8 in. thick. This is underlain by 1 to 10 ft of coarse- to medium-textured fibrous peat. This, in turn, is often underlain by a fairly firm, blue-gray clay and silty clay with thick lenses of dark gray clays and silty clays high in organic content. It is
estimated that only 10 to 20 per cent of fresh- to brackish-water marsh deposits consists of inorganic materials.

**Saline- to brackish-water marsh**

This type marsh typically consists of a mat of roots, stems, and leaves from 2 to 8 in. thick, underlain by a fairly firm, blue-gray clay with a few roots and plant remains. Tiny organic flakes and particles are disseminated throughout. Clays become less organic and firmer with depth. In contrast to other marsh types, a fairly high percentage of inorganic materials imparts some degree of stability to the material. The silt-fine sand content may range as high as 30 per cent. Organic clays make up an average of 50 per cent of the deposit, and peat content normally ranges between 15 and 20 per cent.

**Inland swamp**

Inland swamps in the study area occur almost exclusively in the tree-covered lowlands adjacent to the natural levees. The last such environment along the Mississippi River occurs just downstream from New Orleans. The presence of logs, stumps, and arboreal root systems in the swamp deposits usually permits their identification. Swamp deposits normally consist of less than 30 per cent organic content. Organic material occurs principally in the form of organic and highly organic clays; however, peat and layers of decayed wood are not uncommon. Inorganic content is a reflection of the proximity of the stream that supplies, or once supplied, clays during overbank flow, and organic content can be expected to increase and inorganic content to decrease with distance from such a stream.

**Mangrove swamp**

Only a few small areas of mangrove swamp have been reported in the
study area. Most of these border Quarantine Bay (plate 9). There are conflicting reports concerning the nature and extent of this mangrove area. Apparently, it is ephemeral in nature, bushy mangrove periodically being replaced by grassy marshland. For this reason mangrove areas in plate 9 are shown with an overprint of saline-to-brackish-water marsh. Deposits left by death and decay of the mangrove growth should, however, resemble deposits in mangrove swamps elsewhere in southeast Louisiana. A typical soil sequence in such areas consists of a thin layer of dark gray to black, very soft, organic silty clay covering and forming the matrix for a tangled, interlocking root zone which averages 5 to 12 in. in thickness. Numerous nodular roots project above the surface for a few inches. A thickness of at least 5 ft of organic-rich clays, silts, and sands is typical below this upper layer.

**Engineering characteristics**

Marsh and swamp deposits almost always present problems in foundation engineering. Their high organic content and associated high water content make them very compressible. One of the more striking properties of some marsh deposits is their rapid consolidation immediately upon application of load, such as an embankment. Consolidation and subsidence continue for a long period of time at a gradually decelerating rate. Artificial levees in some areas of south Louisiana, particularly along the East Atchafalaya Floodway, have sunk into the underlying swamp and marsh deposits to such an extent that there is twice as much levee below the surface as there is above.

In many instances the marsh at the surface consists of a mat of roots and grasses underlain by materials which afford no support at all. A person breaking through such a mat can sink waistdeep in ooze.
Metal probes 15 ft long will often sink out of sight under their own weight once the surficial mat has been penetrated. In excavations in marsh areas, a common tendency is for organic oozes, detrital peats, and soft organic clays to flow laterally into open cuts. Spoil from cuts must be spread over as wide a base and as far as practicable from the excavation where such conditions exist. If highly organic materials, particularly peats, are placed in an embankment, shrinkage is considerable, often as much as two-thirds of their former volume.

**Marine Environments**

Marine environments of deposition form only a minor portion of the materials in the bed and banks of the river between Donaldsonville and the Gulf. At least our present knowledge of the distribution of marine deposits in the study area indicates that they are volumetrically unimportant. To date, only the basal nearshore gulf deposits and an equivalent estuarine horizon, the buried beaches, and the bay-sound environment have been identified in the study area.

**Nearshore-gulf, estuarine, and bay-sound**

These three environments consist essentially of shell-bearing sandy and silty deposits. The nearshore-gulf deposits form a horizon which may or may not be present on top of the Pleistocene, its formation and preservation apparently having been dictated by the effect of marine erosion as sea level rose and inundated the Pleistocene surface. It is identified in most of the deeper borings in New Orleans and downstream from New Orleans (see Sections R through DD, plates 26-37). Thicker, analogous deposits fill the numerous drainageways carved into the Pleistocene prior to inundation. These formed gullies or re-entrants
within which, again depending on the rapidity of rise in sea level, sediments were probably laid down under estuarine conditions. Sediments in Section W, plate 30, are interpreted as estuarine deposits from -100 ft msl to a depth as great as -160 ft msl. The upper 10 to 20 ft of this deposit contains clays and, incidentally, wood that has been dated by carbon-14 methods as being 10,000 years old, an age corresponding well with current hypotheses concerning the waning glacial rise in sea level. Bay-sound deposits are identified only in the New Orleans area where conditions existed for the formation of a bay or sound behind the large barrier beach that trends through New Orleans (see following paragraphs).

Beaches

Buried beaches are an integral part of the mass of Recent sediments forming the deltaic plain. As additional data are collected, numerous environments of this sort will undoubtedly be identified and delineated. At the present time, however, only two zones of beach development have been identified in the area studied. One such zone occurs between river miles 20-30 near Head-of-Passes. Most of the evidence for its occurrence is derived from surface indications. There is a well-developed series of abandoned beaches in the marsh to the southwest of this area. These trend eastward becoming indistinct, the surface indications finally disappearing entirely beneath the wedge of the Mississippi fluvial-marine sediments. Few subsurface data are available to substantiate the location of the major sand ridges in this beach zone. Poorly logged shot-point borings indicate a sandy sequence in this region and surface probes by Welder have encountered sands identified as part of this beach system.
An extensive buried beach in the New Orleans area, on the other hand, has not only been delineated, but enough data are now available to contour the deposit. The contours shown in fig. 13 are based largely on work by Saucier. The profile is developed from borings made by Palmer and Baker, Consulting Engineers. Note how the abandoned Metairie distributary lies along the southern edges of the buried beach. Obviously, this feature largely controlled the position and development of this distributary.

Analysis of samples from a number of the presently forming sand beaches in southern and southeastern Louisiana shows them to possess very similar physical characteristics. They consist almost entirely of poorly graded fine sand (90 per cent), about 5 per cent silt sizes, and about 5 per cent shell fragments. Median grain diameters are on the order of 0.15 mm. Eighty per cent of the material ranges from 0.2 to 0.08 mm in grain size. The angle of internal friction typically varies between 30° and 35°. The few samples available of the buried sand beach which trends through New Orleans suggest that the material in this beach is very similar to that in the beaches which presently fringe the deltaic plain. No data are available on the nature of the sand beaches in the study area near Head-of-Passes. In the deltaic plain, where good foundation materials are often at a premium, the occurrence of a buried sand beach at reasonably shallow depths can be a major factor in foundation design and construction costs.

Summary

Fig. 14 summarizes and permits comparison of the ranges of some of the physical properties characteristic of the depositional types
Fig. 13. Contours on top of buried beach in New Orleans area in ft msl and the configuration of a portion of this feature in profile.
### DEPOSITIONAL TYPES

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**LEGEND**

- **Gravel (>2.0 mm)**
- **Sand (2.0-0.05 mm)**
- **Silt (0.05-0.005 mm)**
- **Clay (<0.005 mm)**
- **Organic material**
- **Shell**

- Typical range of values indicated by length of bar. Bar width indicates relative distribution of values.

1. Symbols based on unit.
2. Shearing strengths of

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**Fig. 14. Typical properties of depositional**
Insufficient data for deposition types—Donaldsonville to Gulf

Shearing strengths of clays based on unconfined compression tests.

<table>
<thead>
<tr>
<th>UNIT WEIGHT (LB/FT)</th>
<th>SHEAR STRENGTH (2)</th>
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<tr>
<td></td>
<td>COHESIVE STRENGTH (LB/SQ FT)</td>
</tr>
<tr>
<td>10</td>
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<tr>
<td>80</td>
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<tr>
<td>120</td>
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</tbody>
</table>

(1) Symbols based on unified soil classification system.
(2) Shearing strengths of clays based on unconfined compression tests.

Types of depositional types—Donaldsonville to Gulf
described in this chapter. Much of the data shown in the figure were taken from a similar summary shown in reference 53, which generalized physical characteristics of depositional environments for the whole of southeastern Louisiana. In the present study, samples from borings penetrating individual environments along the river between Donaldsonville and the Gulf were analyzed and compared with results of the previous study. In most instances the ranges of physical properties compared well. In some instances the ranges were changed to more closely reflect the characteristics of the environments which occur along the river.
CHAPTER V

AN EXAMPLE OF FOUNDATION DESIGN PROBLEMS ASSOCIATED
WITH RIVERBANK SOILS

Introduction

Berkey, Terzaghi, Burwell and Roberts, and Banks among others have outlined the responsibilities of the engineering geologist in foundation design. More than 30 years ago, in a passage as timely today as it was then, Berkey described the position of the geologist in the practice of engineering as "analogous to that of an advisor.... It is his duty to discover, warn, explain, without assuming the particular responsibility of the engineer who has to design the structure and determine how to meet all the conditions presented and stand forth as the man responsible for the project."

Thus, although the engineering geologist is expected to understand the fundamentals of design, he is seldom asked to accept—nor should he accept—the responsibility of design of a particular structure. Conversely, the intricacies of sedimentation and soil deposition are peculiarly within the province of the geologist. He is, or should be, responsible for the proper interpretation of the borings, for determining the horizontal and vertical disposition of the strata, for properly assessing anything of a geological nature which may affect design of the structure.

The engineering geologist becomes increasingly more qualified as his knowledge of engineering increases; not because this authorizes
him to assume the duties of the engineer, but rather because it enables him to work more closely with the engineer in his role as advisor. A knowledge of the basis for design permits him to detect the geologic factors at a given site that are pertinent, to point out certain factors concerning stratification which may have escaped the attention of the engineer, and to assist in the planning of a boring program which will aid significantly in interpreting subsurface conditions.

The engineering geologist should be aware that the soil mechanics engineer must base design of earthwork foundations on many simplifying assumptions. He should be constantly alert for geologic evidence which tends to support or preclude the application of standard soil mechanics theory to foundation design. As Terzaghi points out, "As soon as the (engineering) student has left his alma mater he again becomes blissfully unaware of the uncertainties involved in the assumptions on which his computations in subsurface engineering are based and the consequences are deplorable." The experienced engineer is well aware of the limitations in his computations and he is usually eager to learn from the geologist details of stratification which may be particularly significant because of these limitations. Observations of natural slopes in a given area, for example, may cause him to question or modify the slopes he may have assigned for a road cut on the basis of his computations. The failure of an older structure which the geologist knows to have been built on a soil sequence similar to that for which a new structure is being designed may cause the engineer to alter the assumptions on which his bearing capacity computations are based. Such close liaison between the geologist and the engineer results in safer, improved design. It also helps to prevent the common and often very
costly overdesign of structures, where shortening of pile length beneath a large building or the steepening of slopes on an earth dam can save many hundreds of thousands of dollars without endangering the safety of the structures in any way.

The discussion which follows is intended particularly for the geologist interested in knowing in a very general way how subsurface conditions influence the design of a structure. Five typical problems faced in design of a structure are considered: (a) the amount and rate of foundation settlement, (b) bearing capacity of the foundation soils, (c) pile foundations, (d) uplift pressures, and (e) excavation slopes.

**Definitions and Symbols**

This list of symbols and definitions includes only those which are used in evaluating the problems enumerated above. The reader interested in pursuing these problems beyond the simplified treatment presented here should consult any standard text on soil mechanics.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Width of a footing or pile, ft</td>
</tr>
<tr>
<td>c</td>
<td>Cohesive strength, tons or lb/sq ft</td>
</tr>
<tr>
<td>c_v</td>
<td>Coefficient of consolidation. A value, determined in the laboratory, used in settlement computations; expressed in $\text{ft}^2/\text{mo}$ or similar units</td>
</tr>
<tr>
<td>D</td>
<td>Depth of foundation, footing, or pile burial, ft; also, dimensionless value used in slope stability determination</td>
</tr>
<tr>
<td>e</td>
<td>Void ratio. The ratio of the volume of voids to the volume of solids, dimensionless</td>
</tr>
<tr>
<td>e_o</td>
<td>Original void ratio of initial overburden pressure, dimensionless</td>
</tr>
<tr>
<td>e_2</td>
<td>Void ratio at any applied structural load</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Coefficient of friction, dimensionless</td>
</tr>
<tr>
<td>$F_j$</td>
<td>Downward forces</td>
</tr>
<tr>
<td>$FS$</td>
<td>Factor of safety</td>
</tr>
<tr>
<td>$h$</td>
<td>Pressure head, ft of water; also length of pile buried, ft</td>
</tr>
<tr>
<td>$H$</td>
<td>Thickness of soil stratum, ft; also, depth of cut in ft in slope stability determination</td>
</tr>
<tr>
<td>$i$</td>
<td>Angle of inclination of earth slope, degrees</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of a footing or pile, ft</td>
</tr>
<tr>
<td>$m, n$</td>
<td>Dimensionless values used in determining vertical stress beneath uniformly loaded rectangular area</td>
</tr>
<tr>
<td>$N_c$</td>
<td>Stability number used in slope stability problems, dimensionless</td>
</tr>
<tr>
<td>$N_c, N_q, N_γ$</td>
<td>Bearing capacity factors indicating supporting capacity due respectively to cohesion, surcharge, and solid friction, dimensionless</td>
</tr>
<tr>
<td>$P_{ult}$</td>
<td>Ultimate bearing capacity, the loading intensity on a footing or other similar foundation which causes the soil to shear, lb or tons/sq ft</td>
</tr>
<tr>
<td>$P$</td>
<td>Normal pressure, lb or tons/sq ft</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Initial overburden pressure, lb or tons/sq ft</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Total load, lb or tons/sq ft</td>
</tr>
<tr>
<td>$s$</td>
<td>Shear strength, lb or tons/sq ft</td>
</tr>
<tr>
<td>$t$</td>
<td>Time, in days, months, years, etc., settlement analysis</td>
</tr>
<tr>
<td>$T$</td>
<td>Time factor, consolidation theory, dimensionless</td>
</tr>
<tr>
<td>$T_u$</td>
<td>Time factor corresponding to $u%$, or any given percentage of consolidation</td>
</tr>
<tr>
<td>$U\uparrow$</td>
<td>Upward forces</td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical distance, or depth, ft</td>
</tr>
<tr>
<td>$γ$</td>
<td>Unit weight, total saturated or moist weight per unit volume of soil, lb/cu ft</td>
</tr>
<tr>
<td>$γ_e$</td>
<td>Effective unit weight, lb/sq ft</td>
</tr>
</tbody>
</table>
The Problem

Consider a structure (fig. 15) 100 x 100 ft which when completed will exert a pressure of 3 tons per sq ft on the underlying soil. The soil consists of a riverside backswamp clay 60 ft thick underlain by 70 ft of substratum sand down to Pleistocene. To simplify the calculations which follow, the clay and sand are considered to be homogeneous. The water table is at the ground surface.

Fig. 15. Situation at problem site
Settlement

Settlement is defined as the vertical displacement due to elastic deformation and consolidation of the foundation soils as distinguished from displacements resulting from exceeding the bearing capacity of the soil. Uniform settlements up to a foot or more are often permissible except where such settlement creates problems such as disruption of piping systems coming into a building or dislocation of approaches. Differential settlements are almost always troublesome. They may create undesirable stresses on structural members, cause doors to stick and walls to crack, and in extreme cases, cause complete failure of the structure. The design engineer usually assigns a value for maximum settlement which he considers safe from a structural standpoint.

The lateral distribution of environments of deposition which result in variable lithologies thus becomes quite important in design; for example, the delineation of the precise contact between sandy point bar deposits and the highly compressible organic clays of a marsh deposit. A frequent major break in the lateral continuity of soil strata in the delta region is the occurrence of narrow abandoned distributaries or tidal channels filled with materials which usually contrast markedly with the soils which border them. They may vary in width from a few tens of feet to hundreds of feet, and in depth from ten to more than a hundred feet. One such abandoned distributary trends diagonally through a site considered for Violet Lock just downstream from New Orleans. See plates 7 and 29, Section V, for the distribution of this feature in plan and profile. Also note the many analogous features shown in plan in plates 8-10.
In the case of the structure previously described and the soils which underlie it, only settlement or consolidation of the clay layer need be considered. The compressibility of the sand will be negligible and almost instantaneous. Normal practice is to select samples for consolidation tests from the middle of each compressible stratum. Of considerable importance is the selection of samples that are truly representative. Interpretation of soils units encountered in borings in terms of geologic environments of deposition often serves as a guide in selecting samples. If, for example, the massive clay underlying the structure consisted of a lacustrine clay overlying an organic marsh or swamp clay overlying, in turn, a prodelta clay, at least one sample would be chosen from each environment and subjected to laboratory tests for a reasonable estimate of settlement values.

For simplicity, the clay at the problem site is considered homogeneous and normally consolidated. An undisturbed sample is needed from the midpoint of the stratum, the various pressures to which the clay will be subjected must be calculated, and the sample must be subjected to these same consolidation pressures in the laboratory. In this instance there are two pressures involved, namely $P_0$, which is the initial or natural overburden pressure, and $P_2$, the total load after the structure has been built. In cases where there is no preconsolidation, pressure calculations in settlement problems are usually made to the midpoint of the affected stratum.

Amount of settlement

The initial overburden pressure ($P_0$) is calculated by multiplying the submerged unit weight of the clay ($\gamma_{\text{sub}}$) by the depth ($z$) to the midpoint of the clay:
\[ P_o = \gamma_{\text{sub}} \cdot z = 37.6 \times 30 = 1128 \text{ lb/sq ft} = 0.564 \text{ ton/sq ft} \]

The increase in pressure due to the net structural load (\( \Delta P \)) must now be determined from a chart such as fig. 16, which shows the vertical stress distribution beneath one corner of a uniformly loaded, rectangular area (Boussinesq case). Since the problem structure is 100 by 100 ft, units \( x \) and \( y \) on fig. 16 are each 100 ft; \( z \) is the depth to the midpoint of the stratum or, in this case, 30 ft.

Thus,
\[
m = \frac{x}{z}; \quad n = \frac{y}{z}, \quad \text{or} \quad m \text{ and } n = \frac{100}{30} = 3.3
\]

Entering the chart with this value for both \( m \) and \( n \), fig. 16 shows a corresponding value for \( W_o \) of 0.246 and

\[
\Delta P = W \times W_o = 3 \text{ tons/sq ft} \times 0.246 = 0.738 \text{ ton/sq ft}
\]

\( P_2 \), or the load at the midpoint of the clay stratum beneath one corner of the structure, will be

\[
P_2 = P_o + \Delta P = 0.564 + 0.738 = 1.302 \text{ tons/sq ft}
\]

With these two values, \( P_o \) and \( P_2 \), comparable void ratio values \( (e_o \text{ and } e_2) \) can be determined from a pressure-void ratio curve prepared from a consolidation test on the sample. Fig. 17 illustrates such a curve. Pressure (\( P \)) applied to the sample is plotted on a logarithmic scale along the horizontal axis of the plot, and void ratio (\( e \)) along the vertical axis. As the sample is compressed during the consolidation test, periodic readings are taken to determine the reduction in volume and corresponding void ratio of the sample. From this curve the change in void ratio (\( \Delta e \)) between the original void ratio (\( e_o \)) and the void ratio after the structure has been placed (\( e_2 \)) can be determined.
Fig. 16. Vertical stress beneath uniformly loaded rectangular area
Fig. 17. Pressure-void ratio curve of clay sample at problem site. Circles are void ratio determinations for a series of increasingly large laboratory loads on the sample.
The amount of settlement of the foundation stratum ($\Delta H$) is computed according to the formula

$$\Delta H = H \left( \frac{e_o - e_2}{1 + e_o} \right)$$  \hspace{1cm} (1)$$

where $H$ is the thickness of the stratum and $e_o$ and $e_2$ are the void ratios at pressures $P_o$ and $P_2$ (fig. 17). Based on the values taken from fig. 17:

$$\Delta H = 60 \left( \frac{0.980 - 0.890}{1.980} \right) = 2.72 \text{ ft}$$

Settlement beneath the center of the structure is similarly determined. The 100-ft by 100-ft foundation area is divided into four 50-ft by 50-ft areas and the accumulative pressures determined for the common corner at the center of the original 100-ft by 100-ft area.

$$m = n = \frac{50}{30} = 1.67$$

$$W_o = 0.223 \text{ (fig. 16)}$$

$$\Delta P = 3 \text{ tons/sq ft} \times 0.223 \times 4 = 2.77 \text{ tons/sq ft}$$

$$P_2 = P_o + \Delta P = 0.564 + 2.7 = 3.264 \text{ tons/sq ft}$$

Thus the effective pressure beneath the center of the structure and at the midpoint of the clay stratum will be 3.264 tons/sq ft. Based on values taken from the pressure-void ratio curve (fig. 17):

$$\Delta H = \frac{e_o - e_2}{1 + e_o} = 60 \left( \frac{0.980 - 0.775}{1 + 0.980} \right) = 6.24 \text{ ft}$$

This amount of settlement would not be permissible in most structures. Special design of the foundation slab would be necessary. Measures to prevent such settlement include spreading the structural
load over a wider area, e.g., over a 150-ft by 150-ft base, or supporting the structure with piles. This will be considered briefly later in this discussion.

**Rate of settlement (one-dimensional consolidation)**

Rate of settlement is often of considerable importance in design of structures. In rapidly consolidating soils, such as clean sand, the foundation may settle about as fast as the structural load is applied. In some clays settlement may take years. The more impervious the clay, the greater the time required for the water to escape from the pores in the material as it consolidates. Rate of settlement is normally calculated and expressed in terms of the percentage of total consolidation. Since the final 10 per cent of consolidation might require as much time as the previous 90 per cent, a time value for, say 50 or 60 per cent consolidation is usually chosen for calculation according to the following formula:

\[ t = \frac{T_u H^2}{c_v} \]  

(2)

where \( t \) is the time for a selected percentage of consolidation in the field; \( T_u \) is a time factor corresponding to \( u \) per cent of consolidation;* \( c_v \), or the coefficient of consolidation, is obtained from

*The table below lists the commonly used values of \( T \) for various values of \( u \):

<table>
<thead>
<tr>
<th>( u% )</th>
<th>Consolidation</th>
<th>( T )</th>
<th>( u% )</th>
<th>Consolidation</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.008</td>
<td>60</td>
<td>0.287</td>
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</tr>
<tr>
<td>20</td>
<td>0.031</td>
<td>70</td>
<td>0.403</td>
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<td></td>
</tr>
<tr>
<td>30</td>
<td>0.071</td>
<td>80</td>
<td>0.567</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.126</td>
<td>90</td>
<td>0.848</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.196</td>
<td></td>
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</tbody>
</table>
laboratory settlement-time curves of the samples tested; and $H$ is the length of the longest drainage path in feet, in most instances, the distance water at the midpoint of the stratum tested would have to travel to reach a pervious layer or the surface. Under ordinary conditions of two-way drainage $H$ is one-half the thickness of the compressible stratum being investigated.

Using a coefficient of consolidation ($c_v$) of $10 \text{ ft}^2/\text{month}$ characteristically encountered in backswamp clays, and a time factor ($T_u$) corresponding to 50 per cent consolidation, then

$$t = \frac{T_u H^2}{c_v} = \frac{0.196 \times 30 \times 30}{10} = 18 \text{ months}$$

Thus in 18 months the structure would have completed one-half its total settlement (2.72 ft) or 1.36 ft at the corner and half of 6.24 ft or 3.12 ft at the center.

Where settlements are such as to endanger the structure or cause problems with entrance lines, the area is often surcharged with a load of earth to simulate the weight of the structure. Sand drains, i.e., vertical holes filled with sand through which pore-water pressures in the clays can be dissipated, may be used to speed the settlement process.

To illustrate the importance of an accurate interpretation of soil conditions beneath a given site in time-settlement computations, consider the effect of a thin pervious stratum at about the middepth in the 60-ft clay stratum at our problem site. Had such a stratum existed, the value for the drainage path distance would have been slightly more than halved (depending on the thickness of the stratum) and the area would have settled much more rapidly.

$$t = \frac{T_u H^2}{c_v} = \frac{0.196 \times 15 \times 15}{10} = 4.4 \text{ months}$$
The time for settlement, it can be seen, varies as the square of the drainage path distance (H). Thus, proper interpretation of logs of borings coupled with a knowledge of the intricacies to be expected in deltaic and fluvial sedimentation is of considerable importance in time-settlement problems. The design engineer needs to know, for example, that in intradelta complex and interdistributary deposits, stratification is characteristically lenticular. In such instances, a boring program may establish the existence of a permeable sand unit beneath a given site; however, the unit may terminate laterally within only short distances. Fig. 18a illustrates such a hypothetical sand lens beneath the problem structure. Water cannot drain from the permeable sand layer except through the clay which surrounds it. The value of H, therefore, is unaffected by the isolated sand lens and the rate of settlement is less than one-quarter of that which would be determined by calculations which assumed that the sand had a drainage outlet. Differential settlement can also result from lenticular bedding or from an abrupt lateral discontinuity of soil types. Consider fig. 18b, where a lens of sand extends under only part of the structure. The left side of the structure in this instance will settle more rapidly than the right. In fig. 18c, a sandy, abandoned distributary lies just to the left of the structure. Pore-water pressures in the clays which border this sand unit can dissipate horizontally and the clays which border the abandoned distributary would, in such an event, settle more rapidly than those under the remainder of the structure.

**Ultimate Bearing Capacity**

From an engineering viewpoint, one of the most important properties
Fig. 18. Three hypothetical soil sequences that would affect settlement at the problem site. a is an isolated sand lens without a drainage outlet; b is a lens which underlies only part of the foundation; and c is a vertically disposed stratum that would act as a sand drain.
which a soil possesses is shearing resistance or shear strength. The
shearing resistance which a soil may possess under given conditions is
related to its ability to withstand load. It is also of consequence in
determining the stability of slopes. A foundation must be designed so
as to be safe against a shear failure in the underlying soil. This
means that the load which is placed on the soil must not exceed the
ultimate bearing capacity. The application of the theoretical concepts
concerning ultimate bearing capacity yields only approximate results,
and must be used in conjunction with a fairly large factor of safety
in design of foundations.

From the standpoint of ultimate bearing capacity, only the clay
stratum at the problem site need be considered. Its most important
property in these calculations is its shear strength. Natural clays
in the field under saturated conditions, if loaded so rapidly that
little drainage can occur, behave as if they possess no angle of in­
ternal friction (\(\phi\)). This means that the formula which expresses
shearing strength \(s\)

\[ s = c + P \tan \phi \]  \(\text{(3)}\)

reduces to

\[ s = c \]  \(\text{(4)}\)

or that shear strength is equal to the cohesive strength of the clay,
and that neither the effective normal pressure \(P\), nor the angle of
internal friction \(\phi\) is of consequence.

The formula used to express ultimate bearing capacity beneath a
rectangular footing or foundation is as follows:
\[ P_{\text{ult}} = cN_c \left( 1 + 0.3 \frac{B}{L} \right) + \gamma D N_q + 0.4 \gamma N \gamma \]  

(5)

The first term in the equation is that part of the ultimate bearing capacity due to cohesion, the second term is that part due to depth of burial of the foundation and the surcharge effect, and the third term is that part due to solid friction. At the problem site there is no surcharge effect to add to ultimate bearing capacity because the structure is resting on the surface, and there is no increase in strength due to solid friction because a cohesive clay is involved for which the angle of internal friction (\( \phi \)) is 0. The formula, thus, reduces to the first term in the equation, or

\[ P_{\text{ult}} = cN_c \left( 1 + 0.3 \frac{B}{L} \right) \]  

(6)

where \( c \) is the unit cohesion of the clay or 800 lb/sq ft, \( N_c \) is a theoretical value equal to 5.7 in the case of clays with \( \phi = 0 \) (see also fig. 19, page 96), \( B \) is the width of the rectangular foundation and \( L \) the length, or 100 ft and 100 ft, respectively.

\[ P_{\text{ult}} = 800 \times 5.7 \left( 1 + 0.3 \times \frac{100}{100} \right) = 5928 \text{ lb/sq ft} = 2.96 \text{ tons/sq ft} \]

The structure, it will be recalled, will impose a load of 3 tons/sq ft on the soil, and since a factor of safety of 2 is normally applied to this value in clays, the allowable load is only 1.5 tons/sq ft. The soil at the site, therefore, is incapable of safely supporting the structure. Methods for resolving this problem include (a) placing the foundations at some depth below the surface, and/or (b) using a pile foundation.

Bearing capacity, where the soils are variable with depth, is often
based on an average shear strength value of the various strata to a
depth below the base equal to the width of the loaded area. Had the
soils been variable beneath the problem structure, i.e. consisted of a
number of strata of variable lithologic or strength characteristics,
shear strength values would have been averaged to a depth of 100 ft
below the structure. This procedure would have been modified if a mark-
edly weak stratum had existed at a depth greater than 100 ft. If this
stratum had a strength of less than one-third the average strength of
the top 100 ft of strata, the calculation of bearing capacity would have
been governed by the strength of the lower stratum. Although this is
somewhat arbitrary, it approximates bearing capacity values obtained by
the tedious application of more sophisticated methods. Where the impor-
tance of the structure or the complexities in the subsurface warrant it,
the engineer usually bases his design on a circular arc or comparable
method of analysis. Descriptions of these methods can be found in any
standard text on soil mechanics, e.g., Hough, pp 199 to 223.

As in settlement computations, the accurate determination of
bearing capacity depends on a careful reconstruction of subsurface
conditions from logs of borings and geologic inference. It is impor-
tant to realize that every boring record leaves a wide margin for
interpretation unless the geologic conditions are exceptionally
simple. Also, unless care is taken, the choice of samples for
testing and laboratory testing procedures may improperly reflect the
effect of what may be a well reconstructed subsurface profile. Again,
close liaison between the engineer, who realizes the limitations of
laboratory testing, and the geologist, who expects and recognizes the
complexities of natural stratification, is of considerable importance.
Pile Foundations

As mentioned above, the bearing capacity of the soil at the problem site is insufficient to support the structure and the possible use of a pile foundation was recommended. Such piles must be of sufficient length and diameter to safely support the load by skin friction along the piles and the surrounding soil, and/or must extend to a stratum which can support a part of the load through point resistance.

Considering first the possibility of supporting the structure by piles bottoming in clay, the following formula expresses the ultimate bearing capacity of an individual square concrete pile, 1 ft on a side and 40 ft long:

\[ P_{ult} = cB^2N_c + \gamma DB^2 + 4BDs \]

where \( P_{ult} \), \( c \), and \( \gamma \) are parameters previously described. \( N_c \) is a value varying with the shape of the pile,\(^*\) \( B \) is the width and \( D \) is the length of the pile, and \( fs \) is the skin friction, which in clays is usually equal to the unit cohesion \( (c) \) of the clay but should not exceed 800 for steel piles and 900 for concrete or wooden piles. In this case, since the water table is at the surface (fig. 15), the submerged unit weight \( (\gamma_{sub}) \) is used.

Thus,

\[ P_{ult} = 800 \times 1^2 \times 9 + 37.5 \times 40 \times 1^2 + 4 \times 1 \times 40 \times 800 = 136,700 \text{ lb} \]

\(^*\)The value of \( N_c \) (usually 5.7 for foundations in clay with \( \phi = 0 \)) is modified according to the shape of the pile. Reference 54 lists a value of 9.0 for \( N_c \) for square or circular piles.
Each pile, therefore, would support 68 tons through skin friction and a minor amount of point bearing in the clay. The factor of safety used in clay is normally 2; the safe allowable load on each pile should thus be 34 tons. The problem structure with a load of 3 tons/sq ft must support 30,000 tons, and 30,000/34 or 880 piles would be needed. This would require spacing the piles on about 3-ft centers to accomplish the necessary support. Because of overlapping areas of influence around each pile, piles are never spaced at intervals closer than three times the pile diameter. The use of 40-ft-long piles supported by the clay stratum alone would therefore be a marginal consideration or would be ruled out entirely.

When settlement at a site is of critical magnitude, as it is beneath the problem structure, it is advisable to extend the piles to a depth which will provide greater point resistance. In the delta area this usually means to a relatively dense sand stratum or the oxidized Pleistocene erosion surface. Careful investigation is necessary of the stratum which is to provide the point resistance. An important consideration is the prevention of what is known as "plunging." Where a stratum selected for point resistance, for example, is thin and of only moderate strength, the piling may plunge through the stratum into underlying weaker zones, causing failure of the structure. Such weak zones are occasionally and unpredictably found in the Pleistocene, a phenomenon possibly associated with the leaching of connate marine waters from these sediments during drop in sea level and their replacement with fresh water.

Another consideration which favors the extension of the piles to a stratum which will provide greater point resistance is that many
clays are remolded as the piles are driven and lose some of their strength. In some clays the loss of strength is very high. Sensitivity is a parameter used to relate the strength of soil in situ to its remolded strength; it can be determined by laboratory testing. Thus, if the clay beneath the problem structure has a sensitivity of 4—an unlikely situation—the cohesive strength of the clay might be reduced from 800 lb/sq ft to 200 lb/sq ft because of the pile-driving operation.* Substituting this remolded cohesive strength into equation 7 would result in a greatly decreased supporting strength for an individual pile and the necessity of increasing the number of piles roughly fourfold. This would obviously be impractical.

To show the effect of extending the piles to the sand stratum for support and neglecting entirely the effect of skin friction of a possibly sensitive clay, the following formula expresses the load that can be carried:

\[ p_{ult} = \gamma DE N_q + 0.4 E^3 N_\gamma + 4 Bh\gamma (D - h/2) \tan \phi \] (8)

where \( p_{ult} \), \( c \), \( D \), \( E \) and \( \phi \) are parameters previously described, \( N_q \) and \( N_\gamma \) are theoretical values based on \( \phi \) (fig. 19), \( h \) is the length of pile buried in sand, and \( \gamma \) is a weighted submerged unit weight for the clay and sand penetrated by the pile.

Assuming a 70-ft-long pile embedded 10 ft in sand and using the soil values shown in fig. 15, a value for \( \gamma \) must first be calculated. Because the pile is six-sevenths in clay and one-seventh in sand, \( \gamma \) would be

*It should be noted here that many clays in the study area are thixotropic, i.e., they lose strength on being remolded but regain strength after variable periods of time.
Fig. 19. Values used to compute ultimate bearing capacity of piles and of shallow foundations under vertical centric loads

\[
\gamma = 37.6 \left( \gamma_{\text{sub of clay}} \right) \times \frac{6}{7} + 67.6 \left( \gamma_{\text{sub of sand}} \right) \times \frac{1}{7} = 42
\]

and, substituting values in equation 8,

\[
P_{\text{ult}} = 42 \times 70 \times 1^2 \times 35 + 0.4 \times 42 \times 1^3 \\
+ 4 \times 1 \times 10 \times 42 (70 - 5) \times 0.675 = 191,000 \text{ lb}
\]

Thus, each 70-ft pile would support 95 tons, disregarding entirely the frictional effect of the overlying clay. The factor of safety used in sands is 1.5, therefore the safe allowable load would be about 64 tons per pile, and 30,000/64, or 455 piles would be needed.

**Uplift Pressures**

Another way of helping to support the structure would be to reduce the effective weight by placing it in an excavation, say 30 ft deep. The effect of greatest magnitude, since the water table is at the surface in the problem area, is the buoyancy of the structure. This effect is calculated by simply multiplying the pressure head at the bottom
of the excavation by the unit weight of water:

\[
\frac{30 \times 62.4}{2000} = \frac{1872}{2000} = 0.936 \text{ ton/sq ft}
\]

Since the structure imposes a load of 3 tons/sq ft, the net structural load at the problem site would be reduced to 2.1 tons/sq ft. In addition there are surcharge (equation 5) and other effects due to placing the structure within an excavation which further increase the ultimate bearing capacity and allow a larger net bearing pressure.

Placing the structure in an excavation presents problems, however, which must be coped with. One of these is the uplift pressure exerted on the clay at the bottom of the excavation and the possibility of heaving of this stratum during excavation or before the structure is placed. Referring to fig. 15, there is some friction loss of head through the sand between the river and such an excavation; however, such friction loss is disregarded in calculating the factor of safety (FS) at any given depth of excavation. The factor of safety is expressed by comparing the weight of the clay remaining beneath the excavation with the uplift pressure:

\[
FS = \frac{F_{\downarrow}}{U_{\uparrow}} = \frac{\gamma_{\text{sub}} \cdot z}{\gamma_{\omega} \cdot h}
\]

where \( F_{\downarrow} \) is the force exerted downward and \( U_{\uparrow} \) the upward forces calculated in the previous paragraph. The downward forces after excavation and before construction are obtained by multiplying the submerged weight of the clay (\( \gamma_{\text{sub}} \)) and the thickness of the clay beneath the excavation (\( z \)).

\[
FS = \frac{\gamma_{\text{sub}} \cdot z}{\gamma_{\omega} \cdot h} = \frac{(100 - 62.4) \times 30}{62.4 \times 30} = \frac{37.6}{62.4} = 0.6
\]

Since the calculated factor of safety (FS) is less than 1, such an
excavation could be expected to heave badly at bankfull river stage. At some calculable stage below bankfull, heaving of the bottom of the excavation would be no problem. Conversely, rise of the river above bankfull and against the levees would aggravate the problem. If construction were to extend over a period when the river was high, a drainage well system, designed to lower the pressure head at the site to safe values, would be necessary.

**Stability of Slopes**

For illustrative purposes, assume that the situation is such that no dangerous uplift pressures are developed at the site and that the foundation excavation will be made. It would be necessary, in such an event, to calculate the safe side slopes that could be used in the excavation. In dealing with a homogeneous clay with an angle of internal friction \( \phi = 0 \), as at the problem site, the set of curves shown in fig. 20 can be used to determine safe side slopes. Referring to this figure, the formula for calculating the safe slope angle is based on a stability number \( (N_o) \):

\[
N_o = \frac{FS \cdot \gamma}{c} \cdot \frac{H}{c}
\]

where \( FS \) and \( c \) have been previously defined, \( H \) is the depth of cut, and \( \gamma \) is the unit weight of the clay. Assuming a factor of safety \( (FS) \) of 1.5,

\[
N_o = \frac{1.5 \times 100 \times 30}{800} = 5.6
\]

Referring again to figs. 20 and 15, the value \( D \) must first be determined. In this instance we know that a sand layer lies at a
Fig. 20. Stability of simple slopes when $\phi = 0$
depth of 60 ft, the depth of cut is 30 ft, thus,

\[ DH = 2 \times 30 = 60 \text{ or } D = 2 \]

With the stability number \( (N_o) \) of 5.6, note that the curve for \( D = 2 \) gives a slope angle value of 50°. The slope can thus be cut at an angle of slightly less than 1 on 1 with a factor of safety of 1.5.

If the strength of the clay were less, say one-half the selected value of 800 lb/sq ft, the slope angle for a similar factor of safety would be only about 7° or something like a slope of 1 on 8, and slope excavation volumes would be approximately eight times more for the weaker clays than for the high-strength clays.

In nonhomogeneous, stratified soils, such as are common in the delta, either the circular arc or the sliding wedge method of slope stability analysis is used in which a shear strength is assigned to each stratum. Calculations are fairly laborious and an example will not be presented here. It is sufficient to say that assignment of proper shear strength values is most important and requires judgment and experience. Here, again, the geologist can be of considerable assistance in the proper delineation of stratification based on his interpretation of borings and/or his knowledge of environmental conditions.

**Summary**

To recapitulate, some of the most important problems faced in earthwork design in the study area are (a) the amount and rate of foundation settlement, (b) bearing capacity of the foundation soils, (c) the need and the requirements for pile foundations, (d) the effect
of uplift pressures, and (e) the calculation of safe excavation slopes. A familiarity with these design problems enables the geologist to judge the importance of stratification on design and the detail with which stratification must be delineated. It permits him to assist more intelligently in planning boring programs for reconstructing subsurface conditions. Also it often enables him to balance the intangibles in interpreting deltaic stratification against some of the generalizing assumptions that must be made in foundation design. In certain instances the heterogeneity of the soil sequence is such that, once this heterogeneity is established, an extensive boring program to determine the precise nature of stratification or extensive laboratory testing of samples is unwarranted. In such instances appropriately large factors of safety must be used, or design must be based on the most critical of the design assumptions.
Migration of the river in the study area is negligible when compared with that of the river upstream. The narrowness of the river in its lower reaches, its great depth, and its limited lateral movement have been attributed to the great thickness of deltaic plain clays within which it must meander. The control of prodelta and interdistributary clays on river migration is well illustrated in the long, almost meanderfree reach of the river south of New Orleans (river mile 0-78). River migration in this portion of the channel is insignificant. The areal extent of point bar deposits, which reflects the extent of migration, averages only 25 to 30 acres per river mile.

Two additional factors are equally important. One is the length of time the channel has been occupied; the other is the existence of tough Pleistocene deposits into which the river must scour its channel. That part of the river between river mile 189 and Bayou LaLoutre (mile 82, plate 1) has been an active channel for more than 2500 years, and meanders are well established. The river downstream from mile 82 is considerably younger---on the order of 1000 years old or less---and meanders are only in the early stages of development. Comparison of point bar volumes between river mile 189 and English Turn (mile 78) illustrates the importance of the Pleistocene in controlling river migration. Between mile 189 and 157, point bar areas average more
than 450 acres per mile. Between mile 157 and 78 the average is about 200 acres per river mile. In the first reach the river is meandering in backswamp clays and substratum sands; in the second the river must migrate in durable Pleistocene clays which in some areas reach almost to the surface and form a natural revetment against local migration.

Of interest are two bends which interrupt an otherwise almost straight channel between English Turn and Head-of-Passes (see plates 9 and 10). These bends occur near Fort Jackson where there is evidence that buried sand beaches lie across the path of the river and form bed and banks less resistant to river erosion than the cohesive clays which normally characterize the river in its lower reaches. Migration apparently initiated at the points where the path of the river crosses the buried beaches, and is concentrated just downstream from these points. Sand picked up at the beaches is deposited short distances downstream causing a bar around which the thread of current migrates. This causes erosion of the bank opposite the bar and the point bar area develops laterally and downstream from the particular sand deposit where it was initiated. Careful study of these anomalous bends might shed considerable light on the perplexing and controversial problem of how and why meanders originate.

An interesting parallel to this lower portion of the Mississippi River is the Gota River of Sweden. This river has a comparable gradient and is also forming its channel in deep, cohesive clays. Its channel is deep and narrow with widths ranging between 200 and 500 ft and depths between 75 and 50 ft, the greater depths corresponding to the narrower widths. Compare this with a maximum depth on the order of 200 ft and a minimum width of 2500 ft in the lower reaches of the Mississippi.
Suspended load in the Gota is almost nil; bed load is confined to inch-thick layers of sand and gravel that sporadically blanket the clay bottom in certain reaches of the river. There is no meandering and no noticeable tendency toward bank widening. Coarse bed load seems to be carried downstream to the delta without any tendency to segregate, to build bars, or to initiate meanders. The stream is thus a natural flume which is gradually being deepened by attrition--by the slow scouring action of coarse bed load particles on the cohesive clays at the bed of the stream.*

The Lower Mississippi can be considered as a similar flume, but fine sand is being fed into its upper end at a prodigious rate, both as bed load and as suspended load. The amount of such fine sand can be roughly estimated based on figures by Holle and others. Of the 5 1/4 million tons carried yearly in suspension, approximately 7 per cent consists of sand. Add an estimated 10 per cent of the suspended volume as the amount of sand being carried as bed load, and the total reaches some 90 million tons of sand carried to the Gulf each year by the Mississippi River. This volume corresponds fairly closely to the rate of growth of the sand "fingers" or intradelta deposits associated with the distributaries at Head-of-Passes. Of the 90,000 million tons of sand carried by this lower reach of the river in the past 1000 years, it is estimated that less than 20 million tons of sand remain behind in the point bar deposits which border it.

This small amount of point bar deposition is striking. Point bar

*Personal communication from Dr. Åke Sundborg, Institute of Geography, Uppsala University, Uppsala, Sweden.
growth in the central and upper portions of the alluvial valley is sometimes more than 1000 ft per year. Migration of bends between Donaldsonville and the Gulf averages less than 2 ft per year. From the preceding paragraph, it is obvious that this slow growth is not due to lack of sand. It must be attributed to the interrelated effect of such factors as (a) a distribution of velocities capable of keeping fine sand moving downstream; (b) the nonexistence of slack-water areas capable of permitting such fine sizes to be permanently deposited; and (c) the innate resistance of the cohesive banks along the stream to erosion and migration.

Point bars grow where the river deviates from a straight course. If the deviation is gentle, velocities are fairly uniform throughout the channel cross section; or, at least, they are sufficient to continue to move fine sand, and growth is so slow as to be nearly imperceptible. Sharp deviations from a straight-line path permit more rapid bar growth, and along the lower river are associated with such phenomena as faulting, distributary selection, and the location of a coarse deposit along the path of the stream. Faulting, such as has apparently occurred at the large bend just downstream from New Orleans, can radically influence the direction of the stream, causing it to follow an angular pattern which eventually becomes rounded and sinuous through bank erosion and bar building. However, few faults are known to affect the lower river. Fairly sharp deviations from a straight-line path can also occur where the river, in developing its distributary system, selects a distributary for final occupancy which branches at a considerable angle from the general direction of the main channel. This, again, is an abnormal situation since a large angle of bifurcation from the main channel is
one of the primary reasons for the river's ultimate abandonment of a distributary. A third reason for development of a bend is the occurrence, entrainment, and deposition of relatively coarse materials, such as might exist in a buried beach along the course of the stream.

Once the bend is established maximum velocities hug the outside of the bend, and minimum velocities on the inside of the bend are low enough for occasional deposition of fine sand and silt. The point bar grows at a gradually increasing rate as the curvature of the bend increases, and the incidence of low velocities at the bar increases.

But, as has been previously stressed, this rate of growth is remarkably slow in the study area. The essentially straight reaches can be expected to remain straight for decades. The sharpest bends, the most upstream bends, and bends opposite or immediately downstream from a bank cutting into easily erodible point bar deposits can be expected to migrate most rapidly. In the study area, the river is cutting into point bar deposits principally between river miles 181-188 upstream from Donaldsonville (plate 3), and since this is predominantly silty point bar material, the products of bank erosion contribute little to over-all bar building downstream. Where it scours deeply enough to intercept the substratum, the river picks up sand that might, occasionally, be coarse enough to contribute to over-all downstream bar building. But even this source is lost downstream from College Point. The sand available for the river to carry in its lower reaches is of such small grain size that the vast majority can be carried almost uninterruptedly to the delta. There is thus no reason to believe that the rate of river migration will change within the next century, or several centuries, from the very slow rate that has characterized the lower river in the past.
In summary, migration of the Mississippi River channel between Donaldsonville and Head-of-Passes has been affected by such factors as
(a) length of occupation, (b) the extensive occurrence of clays forming its bed and banks, particularly of Pleistocene clays, (c) the occurrence of bends caused by faulting or formed during seaward growth of the delta, and (d) the occasional existence of coarse or easily erodible materials in the path of the stream. Samples of bed material, the material which forms the point bar areas, and most significant of all, the material comprising the delta, show that nothing coarser than fine sand is introduced into the lower river channel in any significant quantities. The vast majority of the bed and suspended load is carried to the delta without contributing to the growth of the point bar areas. Finally, the rate of migration in the lower river has been and should continue to be very slow.
CHAPTER VII
SUMMARY AND CONCLUSIONS

Plates 3-39 show the distribution of engineering soils which border the Mississippi between river mile 189 and Head-of-Passes in plan and profile. Interpretations shown on these plates are based on all available boring data, and although many of the details of the disposition of soils units have yet to be learned, the broad outlines have been fairly well confirmed and delineated. An increased knowledge of the sedimentary sequence will result from further analysis of boring data and a better understanding of the geologic history of and the depositional processes active in the deltaic plain. The engineering soil types can be readily and advantageously associated with the environment within which each was deposited. Delineation of environments of deposition permits reasonably accurate estimates of subsurface soil types, typical ranges of many of their physical properties, and their distribution in plan and profile. Conversely, physical properties of soils encountered in bore holes are sufficiently diagnostic so that environments within which they were deposited can usually be determined. This permits reconstruction of buried environments based on fewer and more carefully located borings.

Some significant points learned in this investigation are as follows:

a. The Mississippi River flows across a "shelf" of shallow
Pleistocene deposits between College Point (river mile 157) and English Turn (river mile 78). This shelf is far less dissected than was thought heretofore. The depth to this horizon between the two points mentioned varies from 0 to 150 ft.

b. The concept of backswamp deposits underlain by coarse substratum deposits loses its usefulness in interpreting logs of borings downstream from College Point. Instead, boring information must be interpreted solely in terms of environments characteristic of the deltaic plain.

c. Point bar deposits form fairly significant wedges of sediment flanking the river as far downstream as New Orleans. Only minor point bar areas occur between New Orleans and the Gulf. No trend toward a decrease in grain size in a downstream direction was noted in the point bar deposits. An expected slight increase in grain size with depth was noted. Point bar deposits consisting almost entirely of silt are found in some areas. The fineness of the deposit, the position of the deposit with respect to the more characteristic sandy point bar, and the tight curvature of the meander scars left by these deposits suggest that they are older deposits left by a smaller stream than the present Mississippi.

d. The existence of a well-defined buried beach trending through the New Orleans area has been fully confirmed and its extent and thickness mapped. The surface of this feature has been contoured in fig. 13.

e. Prodelta clays form a homogeneous wedge of fine-grained sediment encountered at a depth of -40 ft msl in the New Orleans area and at -90 ft near Head-of-Passes. The unit thickens from approximately
40 ft to 140 ft within the same distance.

f. River migration is most noticeable between river miles 189 and 156 where the river is migrating into substratum sands, back-swamp clays, and silty point bar deposits. It is less rapid where it must cut its channel into the Pleistocene deposits between river mile 156 and 78. Migration of bends between Donaldsonville and the Gulf averages less than 2 ft per year. There is no reason to believe that the rate of river migration in the lower river will increase markedly from the very slow rate which has characterized it in the past.

**Recommendations for Future Study**

It is felt that the present study provides a convenient framework into which future geologic and soils data can be integrated. Future studies which would permit a more comprehensive evaluation of the distribution of depositional environments and their associated soil types within the study area include the following:

a. Continued revision, as more data become available, of the contours on the Pleistocene surface and the disposition in plan of the point bar materials bordering the river.

b. Detailed study of the stratification and depositional and engineering characteristics of point bar deposits. Investigations should be made of the occurrence and origin of silty point bar deposits.

c. Analysis of returns from substratum borings to determine the existence of a zone tending to confirm or disprove a marine still-stand at -250 ft msl or equivalent level. Data should also be collected on the occurrence of coarse to medium sand sizes within the substratum.

d. Determination of the distribution and environmental
significance of microfauna, particularly the ostracods, in a number of borings in the area bordering the river between College Point and New Orleans where overlapping alluvial, deltaic, and marine environments of deposition complicate the delineation of engineering soil types.

e. Careful analyses of prodelta clays and silty clays to determine the interrelation of such factors as flocculation, strength, geologic age, and salinity of the water within which the clay was deposited.

f. The development of a classification of the swamp and marsh environments which may be more useful for engineering purposes than the one included in this report.

g. Study of the distribution of soft unoxidized zones within the Pleistocene and the reasons for the erratic distribution of oxidized zones.

h. Continued collection and evaluation of data on the processes of formation, lithology, and engineering properties of environments of deposition within the study area. This involves developing a comprehensive chronology for the sequence of geologic events in the formation of the deltaic plain.
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SOILS CLASSIFICATION SYSTEM BASED ON GRAIN SIZE

NOTE: SOILS TRIANGLE CLASSIFICATION BASED ON PER CENT BY WEIGHT OF SAND, SILT, AND CLAY. SAND RANGE FROM 2.000-0.060 MM IN DIAMETER, SILT BETWEEN 0.060-0.005 MM, AND CLAY < 0.005 MM.

CONSISTENCY FOR COHESIVE SOILS

<table>
<thead>
<tr>
<th>CONSISTENCY</th>
<th>COHESION FROM UNCONFINED COMPRESSION TEST LB/SD FT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERY SOFT</td>
<td>&lt; 150</td>
</tr>
<tr>
<td>SOFT</td>
<td>150 - 300</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>300 - 1000</td>
</tr>
<tr>
<td>STIFF</td>
<td>1000 - 2000</td>
</tr>
<tr>
<td>VERY STIFF</td>
<td>2000 - 4000</td>
</tr>
<tr>
<td>HARD</td>
<td>&gt; 4000</td>
</tr>
</tbody>
</table>

NOTE: CONSISTENCY OF COHESIVE SOILS SHOWN ON THE BORING LOGS IS BASED ON DRILLER'S LOG AND VISUAL EXAMINATION AND IS APPROXIMATE, EXCEPT WITHIN THOSE VERTICAL REACHES OF THE BORINGS WHERE COHESIVE STRENGTHS FROM UNCONFINED COMPRESSION TESTS ARE SHOWN.

DETAILED LEGEND
FOR PLANS AND SECTIONS
LEGEND

- INLAND SWAMP
- FRESH WATER MARSH
- FRESH TO BRACKISH WATER MARSH
- POINT BAR
- ABANDONED COURSE OR DISTRIBUTARY

DISTRIBUTION OF DEPOSITIONAL TYPES
RIVER MILE 114.3 TO 139.7

SCALE IN MILES

PLATE 5
LEGEND

- INLAND SWAMP
- FRESH WATER MARSH
- FRESH TO BRACKISH WATER MARSH
- POINT BAR
- BURIED BEACH
- ABANDONED COURSE OR DISTRIBUTARY

NOTE: SEE PLATE 4A OF WES TR NO. 3-483 FOR ADDITIONAL BORING DATA
SEE PLATE 2 FOR COMPLETE LEGEND
DISTRIBUTION OF DEPOSITIONAL TYPES
RIVER MILE 43.4 TO 63.9
SCALE IN MILES
PLATE 8
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 3 FOR LOCATION OF SECTION.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 3 FOR LOCATION OF SECTION.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 3 FOR LOCATION OF SECTION.
REWORKED PLEISTOCENE

SWAMP-MARSH

MISSISSIPPI RIVER

LEVEE

NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 3 FOR LOCATION OF SECTION.

SECTION G

PLATE 16
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 4 FOR LOCATION OF SECTION.

SECTION I

PLEISTOCENE
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 4 FOR LOCATION OF SECTION.
OXIDIZED - UNOXIDIZED
MED FROM BIUGR
SWAMP MARSH

CLAY 1 FINE

BASED ON HAND-AUGER BORINGS AND ORIGINAL INTERPRETATION
MADE BY ROGER SAUCIER, LOUISIANA STATE UNIVERSITY.

UNDIFFERENTIATED

PLEIST

DISTANCE IN F
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 4 FOR LOCATION OF SECTION.
SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 3 FOR LOCATION OF SECTION.

SECTION M

PLATE 22
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 5 FOR LOCATION OF SECTIONS.

SECTIONS O AND P

PLATE 24
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 6 FOR LOCATION OF SECTION.

SECTION Q

DISTANCE IN FEET

PLATE 25
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 5 FOR LOCATION OF SECTION.
MISSISSIPPI RIVER

NATURAL LEVEE

MLW 0 FT

NATURAL LEVEE

Minn

NATURAL LEVEE

MT

M CLAY LAYEM

P O I N T

B A Y - S O U N D

B A R

SECTION S

DISTANCE IN FEET

ELEVATION IN FEET MSL

ELEVATION IN FEET MSL

DELTA

PRO-DELTA

INTRA-DELTA

SWAMP-MARSH

NATURAL LEVEE

DELTA

BAY-SOUND

PRO-DELTA

SECTION S

DISTANCE IN FEET

ELEVATION IN FEET MSL

ELEVATION IN FEET MSL

ELEVATION IN FEET MSL
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 6 FOR LOCATION OF SECTIONS.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 7 FOR LOCATION OF SECTION.
APPROXIMATELY 10,000 YEARS OLD (C-14 DATE)
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 7 FOR LOCATION OF SECTION.

SECTION W

PLATE 30
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 7 FOR LOCATION OF SECTION.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 8 FOR LOCATION OF SECTION.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 9 FOR LOCATION OF SECTION.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 9 FOR LOCATION OF SECTION.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND AND PLATE 10 FOR LOCATION OF SECTION.

SECTION FF

PLATE 39
MISCELLANEOUS BORINGS
BORINGS 30.8-84.0

NOTE: SEE PLATE 2 FOR COMPLETE LEGEND.
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND.

MISCELLANEOUS BORINGS
BORINGS 133.3-163.3

PLATE 42
NOTE:  SEE PLATE 2 FOR COMPLETE LEGEND.

MISCELLANEOUS BORINGS
BORINGS 170.6-MS-6
NOTE: SEE PLATE 2 FOR COMPLETE LEGEND.

MISCELLANEOUS BORINGS
BORINGS MS-9 - MS-25

PLATE 44
Charles R. Kolb was born in Vicksburg, Mississippi, on 14 April 1920. He attended St. Aloysius High School at Vicksburg and was graduated from there in 1936. From 1937 to 1941, he attended part- and full-time courses at Louisiana State University and George Washington University. He entered the Army Air Corps early in 1942, where he served principally as navigator and bombardier on a B-29 crew. He held the rank of captain at the end of the War and his decorations include: Air Medal with 4 oak-leaf clusters, Distinguished Flying Cross with 2 oak-leaf clusters, Presidential Citation with 1 oak-leaf awarded by War Department in 1944.

He re-entered LSU at the end of World War II where he received his B.S. in Geology in 1948 and his M.S. in 1949. He had worked on a part-time basis with the Geology Branch, U. S. Army Engineer Waterways Experiment Station, while attending the university, and began full-time employment upon graduation from Louisiana State University. He was made Chief of the Branch in 1956 and has served in that capacity since that time.

He was married to Bertha Ragsdale in 1951. They have one son, Chuck, age 9.
Candidate: Charles R. Kolb

Major Field: Areal Geology

Title of Thesis: Distribution and Engineering Significance of Sediments Bordering the Mississippi from Donaldsonville to the Gulf.

Approved:

James P. Morgan
Major Professor and Chairman

Max Goodrich
Dean of the Graduate School

EXAMINING COMMITTEE:

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B.J. Carrington
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C.O. Durham Jr.

Date of Examination:

Jan. 12, 1962