DRAINAGE-INDUCED LAND SUBSIDENCE IN METROPOLITAN NEW ORLEANS, LOUISIANA, U.S.A.

Jesse O. Snowden
University of New Orleans
New Orleans, Louisiana

Abstract
At least two thirds of metropolitan New Orleans is built on reclaimed interdistributary marshes of an abandoned lobe of the Mississippi River Delta. Interdistributary marshes in this region are characterized by accumulations of marsh-grass peat up to five meters in thickness, often interbedded with thin layers of fine silt and clay. Loss-on-ignition analyses reveal that the peat is typically 70 to 80 percent organic matter by dry weight. Below the water table it is approximately 85 percent water by weight.

The marshland was reclaimed by pumped canal drainage, lowering the water table by as much as three meters, and the addition of land fill to compensate for initial subsidence. However, the drainage and land filling process itself causes three types of land subsidence: (1) primary consolidation of the drained peat and underlying clay strata, (2) secondary compression of the peat and underlying clay from the loading of land fill and drained peat, and (3) oxidation of the drained peat.

The low bearing strength of this material requires that buildings be supported by pilings driven at least 12m deep into more competent underlying clay units. Properly spaced pilings stabilize foundations, and, to a degree, retard subsidence directly under buildings, whereas maximum subsidence continues in adjacent areas not protected by pilings. This differential subsidence between buildings and adjacent land results in stress and structural failure of driveways, sidewalks, and most importantly, the rupture of underground utility pipes.

Differential subsidence of up to one meter has been measured, and the amount of differential subsidence correlates closely with sediment type, the amount of water table lowering, and elapsed time since land reclamation. Thus, it is possible to predict areas of existing and future development that will experience hazardous differential subsidence.

Introduction
The city of New Orleans was founded in 1718 as the southernmost port of the Mississippi River where goods could be transferred to and from river boats serving the vast interior Mississippi Valley. The original city was built entirely on the "natural levee", the ridge of silty sediment that borders each side of the river. At New Orleans the highest part of the natural levee is about 5m above sea level; therefore, the levee provided a relatively dry and firm foundation for build-
ing and, when augmented by a low artificial levee system, a measure of protection from flooding. The city was isolated from "mainland" Louisiana by cypress swamps and grassy marshes on the east and west and by Lake Pontchartrain on the north. Thus for nearly two hundred years New Orleans was an "island city" accessible only by the river, the coastal water routes, and the shell roads (frequently washed-out) built on the natural levees. The strategic location of the city, however, more than offset the natural difficulties, and New Orleans grew rapidly. Census figures show that almost from its beginning, New Orleans was one of the largest cities in North America. By 1835, it was virtually in a tie with Philadelphia for second place in population among American cities, and it remains today among the twenty largest metropolitan areas in the United States (Lewis, 1976).

Until the early 1900's the city was restricted to the relatively narrow levees of the Mississippi. This situation changed abruptly when inventor-engineer Baldwin Wood designed a heavy-duty pump that made it possible to quickly raise huge volumes of water a short vertical distance. Drainage canals were dredged through the cut-over cypress swamps north of the city, and Mr. Wood's pumps were used to drain the land. Artificial levees were constructed to protect the newly drained land from flooding. By 1920 developers were building on this land, much of it near or slightly below sea level. It was soon discovered that conventional houses could be built successfully in the drained swamp lands without the use of pile-supported foundations. Construction continued until shortly after World War II, by which time most of the old cypress swamp had been reclaimed and developed.

The remaining undeveloped "land" in Orleans and adjacent Jefferson Parishes was the brackish-water marsh along the southern shore of Lake Pontchartrain. This marshland was drained by the same type of canal-and-pump system which had been used earlier in the cypress swamp. However, the area is underlain by as much as 5m of marsh-grass peat, which proved a poor substrate for construction. Subsidence of the land surface became a major problem in the newly drained areas because the underlying organic-rich sediment was easily compressed. Today large parts of the New Orleans metropolitan area must still cope with the damage caused by sinking land.

Geologic Setting
From the beginning, the way of life in New Orleans was greatly influenced by the underlying geology. The location of early settlements, the style of buildings, the routes of streets and highways, the drainage systems, and even the patterns of ethnic populations in older parts of the city, all are reflections of the geology of the Mississippi River Delta.

The delta is constructed of billions of tons of mud and sand that were eroded from the interior of our continent, transported southward by the Mississippi River, and dumped where the river entered the sea. The flat, low-lying land area built seaward by the deltaic accumulation is a complex of stream channels, levees, swamps, marshes, and lakes, the whole
of which is called the "delta plain". Figure 1 shows a portion of the Mississippi River Delta Plain in the vicinity of New Orleans. The Mississippi River Delta region of southern Louisiana is quite young, geologically speaking, and the deltaic sediments are still soft and unconsolidated.

Recent Geologic History of New Orleans

During the Wisconsin Glacial Stage, the area that is now southern Louisiana stood perhaps a hundred meters above sea level. Then, about 10,000 to 15,000 years ago, the eustatic rise in sea level began to affect the region. Gulf water flooded the New Orleans area about 5,000 to 6,000 years ago, and the Mississippi River began to build its delta in the area southeast of Lafayette, La. In the last few thousand years the river has changed course several times, and deltas have accumulated at various sites from Franklin, La., to south of Biloxi, Miss. The flat low-lying land area built seaward by the deltaic accumulation is a complex of stream channels, natural levees, swamps, marshes, and lakes—the delta plain (Figure 2).

5,000-6,000 years ago, before the beginning of extensive deltaic sedimentation in the vicinity of New Orleans, a series of northeast-southwest-trending sand deposits extended from the Mississippi coast well into the New Orleans metropolitan area. These are barrier-island, bar and shoal sands that were drifted westward by longshore currents. Saucier (1963) called these sands the "Pine Island beach trend." Although this sand trend was buried by younger Mississippi Delta sediments, it is now in many places only a few meters below the surface, and thus strongly influences subsurface engineering properties. Figure 3 is a map showing the location of these buried barrier islands, along with the Pleistocene land surface contours and several more recent geologic features.

As the river continued to deposit sediments at its mouth, land masses grew progressively farther seaward. But the great weight of the deltaic sediment also caused sinking of Earth's crust beneath the delta complex. When the river changed course upstream and abandoned a deltaic lobe, that part of the delta plain continued to subside, becoming progressively more inundated by the Gulf.

Deposition of the St. Bernard lobe of the Mississippi Delta began in the New Orleans area about 4,700 to 4,500 years ago. It is important to understand the stages of deposition and resulting sediment types, because those sediments now make up the land surface and shallow subsurface of New Orleans.

An upstream diversion—similar to the one presently affecting the Mississippi as the Atchafalaya River enlarges—initiated each of the pre-modern Mississippi River courses. Stream capture was a gradual process involving increasing flow through a divergent arm, which offered a shorter route to the Gulf. After capture was effected, each new course lengthened seaward by building a shallow-water delta and extending it gulfward. The onshore part of the delta surface consists of stream channels, called distributaries, which are flanked by low natural levees. Between the distributaries are troughs.
FIG. 2 Multiple Deltas of the Mississippi Deltaic Plain
(from Kolb and van Lopik, 1958)
FIG 3. Major geologic features of metropolitan New Orleans. Numbered contour lines represent the depth below mean sea level of the buried late Pleistocene land surface. These contours also show the land surface as it was 5,000-6,000 years ago. Other features shown are: the buried islands discussed in text; abandoned St. Bernard Delta distributary channel deposits of the modern Mississippi River. The dashed line in Lake Pontchartrain is a major east-west trending fault that was active during late Pleistocene time (adapted from Kolb, Smith and Silva, 1975).
that hold near-sea level marshes and bodies of shallow water. Channels of principal distributaries extend across the gently sloping offshore surface of the delta to the inner margin of the steeper delta front, where the distributary-mouth bars are situated. The offshore channels are bordered by submarine levees, which rise slightly above the offshore extensions of the inter-distributary troughs.

As it lengthens its course, the river occupies a succession of distributaries, each of which is favorably aligned to receive increasing flow from upstream. The favored distributary gradually widens and deepens to become the main stream. Its natural levees increase in height and width, and marshland develops in the troughs adjacent to the distributary. Levees along the main channel are built largely during flood stage. Crevasses create abnormally wide sections of the levee and of adjacent mudflats and marshes, and some of the crevasses continue to remain open and serve as minor distributaries while the levees increase in height. Crevasses also occur along the main stream during flood stage and permit tongues of sediment to extend into the swamps and marshes for considerable distances beyond the normal toe of the levee.

Distributaries with less-favorable alignment are abandoned during the course-lengthening process, and their channels are filled with muddy sediment. The marshlands below New Orleans are beined with abandoned distributaries associated with development of the Mississippi's present course.

The continual migration of various environments of deposition produces a highly complex body of sediment. The sediment type under the delta plain varies from place to place and from depth to depth. Most of the sediments are fine grained throughout the region, reflecting the type of sediment load transported by the Mississippi while the deltaic plain was being built. About 75% of the present-day river load is silt and clay; the remainder is fine sand. Sands are deposited in bars at the mouths of distributaries and in thin sheets spread by marine currents at the delta front. Natural-levee deposits are wedges of silty clay that reach a maximum thickness of 9m at the margins of main channels and thin away from the channels. Organic-rich muds that were deposited on mudflats and in marshes and swamps fringe the natural levees.

Accumulations of peat and organic muck are widespread in several sections of the coastal Louisiana lowlands. Data from many borings provide details concerning local distribution of the deposits in the deltaic plain. The peats range in thickness from a few centimeters to more than 6m, depending on the duration of organic accumulation and the amount of local subsidence. Peat is largely confined to intersistributary troughs of abandoned deltas where continued subsidence allowed marshes to flourish for long periods. Generally, the thickest peat deposits are in the levee-flank depressions along the active and abandoned minor river channels.

The diagrams of Figure 4 show stages in the development of a typical peat deposit; they indicate the changing character of vegetation during levee enlargement and after abandonment of the distributaries.
Fresh-water plants are first to appear on mudflats in the delta (Figure 4a). Peat begins to form from the remains of cat-tails, sedges, and grasses in slightly brackish marshes no more than 0.5m above sea level (O'Neil, 1949). Marshes develop over broad areas within the interdistributary troughs during enlargement of the levees (Figure 4b). In the central part of the trough, in areas removed from river sedimentation, peat may develop entirely from marsh vegetation as the trough subsides. Along the margins of a subsiding trough, the organic accumulations reflect a progressive change in vegetation accompanying levee enlargement, from fresh-water marshes through cypress-gum swamps to brackish and saline marshes. Swamps developing in levee-flank depressions shift toward the center of an interdistributary trough while a distributary enlarges and its levees widen (Figure 4c). After a distributary is abandoned and river sedimentation ceases, continued subsidence of the levees and adjacent trough results in a progressive change from swamps to brackish-marine and saline marshes (Figure 4e). Finally, enlargement of the water bodies obliterates the marshes, and peat accumulation ceases.

Wave action and flooding associated with the enlargement of the coastal water bodies may destroy peat accumulations, or it may bury them with marine silts and sands. For example, peat underlies a thin cover of sandy marine sediment in the northern part of Chandeleur Sound (Kolb, 1958). Some of the sands derived from destruction of the deltaic plain by marine processes are swept to the gulf shore where they are incorporated in delta-martin islands. Typical of these is Grand Isle southwest of New Orleans, where sand more than 10m thick rests upon peat-bearing marsh deposits (Fisk, 1955).

Land Subsidence in Metropolitan New Orleans

Subsidence, the relative lowering of the land surface with respect to sea level, is a natural consequence of deltaic sedimentation in the New Orleans area. Surface and subsurface drainage and development in the city also have caused the surface to subside at an increasing rate. The amount and rate of sinking relate to the complex geology of the delta.

Saucier (1963) calculated the average rate of general subsidence in the New Orleans area to have been 12cm per century for the past 4,400 years. This figure is based on radiocarbon dates of peat deposits and does not include the estimated rate of sea-level rise during this period. On a smaller scale, the process is acting on individual landforms at different rates. For example, natural levees and barrier sands, due to their higher bulk density, may actually subside faster than surrounding clay and organic sediments.

According to Terzaghi (1943) land subsidence occurs as a result of three principal causes (see also ASTM, 1965):

1. Primary consolidation is the reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to a squeezing out of water from the void spaces of the mass.
(2) Secondary compression is the reduction in volume of a soil mass caused by the application of a sustained load to the mass and due to the adjustment of the internal structure of the soil mass after the water is squeezed out.

(3) Oxidation of organic matter results in the reduction in volume of a soil mass as chemical reactions occur which cause the organic matter to decompose into its mineral constituents.

When the level of the groundwater (water table) is lowered, the material above the new water table is no longer buoyed up by the subsurface waters. Therefore, an increased load is placed upon all material below the new water-table elevation. Deep strata, both organic and inorganic, then undergo primary consolidation and secondary compression over a period of years. Additional compaction and subsidence are caused by the interaction of oxidation and secondary compression in the material above the new water table. Whether the volume change is due to primary consolidation, secondary compression, or oxidation of organic matter, the total amount of subsidence is directly dependent upon the level to which the water table is lowered by drainage.

Relationship of Subsidence to Sediment Type
When a part of a delta is drained for urban development, such as in metropolitan New Orleans, subsidence may be generally accelerated, and different rates among the deltaic sediment types are very apparent:

(1) The natural levee-crevasse silts and sands are affected the least. As these deposits formed the high ground (up to 5m above sea level), most were not completely water saturated at the time of development. Further, as these coarser sediments have a grain-support internal structure, they are only slightly affected by dewatering of pore spaces. The same is true of the barrier-island sands.

(2) Backswamp and interdistributary-trough clay deposits, which underlie much of the cypress swamp (Fig. 4) in the New Orleans area are subject to shrinkage upon drying, as the internal structure of these clays is partly water-supported. However, the low permeability of these clays usually prevents them from drying to more than a few feet below their exposed surface, and, therefore, subsidence is often minimal. Where the organic matter in these clays is more abundant their subsidence potential is increased because the organic matter increases permeability and allows deeper drying. Buried logs and stumps in these deposits may provide pathways for moisture loss, and they decompose when exposed to air, thus causing irregular hummocky subsidence.

(3) Peat deposits in the marsh area (Fig. 4) are highly permeable and have by far the greatest potential for subsidence when drained. Particularly large amounts of subsidence occur when the upper peat is left exposed to the atmosphere and shrinkage occurs. Desiccation (drying) of the highly organic soils results in extremely large capillary forces acting to
FIG. 5. Shrinkage test results.
compress the upper layers of soil. The compressive forces are much greater than those imposed by the overburden so that the soils are overconsolidated to the point of forming a stiff upper crust. The desiccation also allows oxidation of the organic matter to occur. Although decomposition contributes to the volume change of the upper organic layers, the shrinkage caused by the large capillary forces associated with desiccation appears to be the predominant factor. This is illustrated by the shrinkage test results presented in Figure 5. Shrinkage tests were performed on organic soils by determining the volume of large undisturbed samples with vernier calipers as the samples were allowed to air dry. The samples were weighed in order to determine the water content corresponding to each volume determination. Representative results are presented in Figure 5 as percentage of original volume versus water content. The original volume was taken as that volume at the natural water content. The results generally show a shrinkage to an ultimate volume of 25 to 30 percent of that volume corresponding to a natural water content of 250 percent. The shrinkage would be even greater if the natural water content were greater than 250 percent. These tests were performed over approximately a 2 week period so that decomposition was not a major contributor; the organic content before and after the test was essentially the same.

General History of Subsidence Problems in New Orleans

Prior to the mid-1950's, most of the construction in metropolitan New Orleans had been on the natural levees of the present Mississippi River and its former distributary. A few subdivisions had also spread into the drained cypress swamp. Most residential construction was on raised-floor foundations, supported by masonry pillars. Sometimes wooden pilings were driven to support the foundation pillars, but more often they were not. Most of these homes are still standing, although irregular subsidence requires periodic foundation levelling in some neighborhoods.

An unfortunate coincidence was the widespread change to the concrete-slab foundation system by residential contractors at the time of urban development of the marshlands in the New Orleans area. Some of the early construction of the reclaimed marshland proved disastrous. The soft spongy peat failed to support heavy concrete slabs, which simply sank into it, occasionally tilting and breaking in the process. It was soon discovered, however, that if enough wooden pilings were driven 10 to 15m through the peat into the clay below, the friction on these pilings would support the slab. In February of 1979, some 25 years after the initial development of marshlands, the Jefferson Parish Council passed an ordinance requiring residential contractors to use pilings in the thick-peat areas of the Parish.

As had been the case in the cypress swamps reclaimed earlier, the drained land surface of the marsh is so low and so hummocky that it is necessary to add up to 1m of fill to level and ele-
Concrete Slab

Differential

FIG. 6. Section of slab-on-piling construction showing differential subsidence.

vate building sites. This is usually done on a lot-by-lot basis, and a variety of fill materials have been used, ranging from broken concrete and asphalt to topsoil. Sand dredged from the Mississippi River or other nearby river channels is the prevalent fill material for residential sites at the present. Figure 6 is a cross section of the slab-and-piling foundation, which has been used for residential construction in the reclaimed marshland since the late 1950's.

Differential Subsidence
Probably the greatest single problem has not been the general areal subsidence but the difference in subsidence between houses on pile foundations and the surrounding ground surface. When houses or buildings are constructed using the slab-on-pilings technique, the foundation is stabilized, but the area surrounding the building continues to subside, thus producing differential subsidence. Many homeowners fill their yards with 10 to 20 cubic meters of soil each year to compensate for this differential subsidence.

Figure 6 shows a representative cross section of a house foundation on piles and the surrounding area after differential subsidence has occurred. A gap may occur under the house slab, but generally the material immediately surrounding the piles adheres to the piles so that the gap beneath the slab is much less than the total differential subsidence. Because the material near the pile foundation is actually supported to a certain extent by piles, the effect is usually one of greater surface subsidence farther from the house. The most important factor is the magnitude of the differential subsidence between the house slab and the surrounding area.
Hazards and Damage Due to Differential Subsidence

Major effects of subsidence have been widespread damage to sewer-, water-, and natural-gas lines, and to streets, driveways, and sidewalks, as well as to structures. Recent case studies have revealed tilting of houses over filled canals, negative skin friction on poles, cracked slabs, and other types of structural distress. The general difficulties are too numerous and the complete ramification of subsidence damage is too lengthy to present in this paper; only the worst hazard caused by differential subsidence will be discussed.

As troublesome as subsidence-caused maintenance problems are, the greatest hazard in the marshland peat area is from natural-gas explosions. Gas and other utility lines are buried in the peat. The stress created by differential subsidence is sometimes enough to rupture gas lines, releasing gas into the highly permeable drained peat. If the fill layer is less permeable than the peat, the gas may migrate some distance, eventually accumulating under a concrete slab foundation. Since 1972, five homes have been destroyed by natural-gas explosions. Figure 7 is a map published by Louisiana Gas Services Company showing measured differential subsidence.

FIG. 7 Measured differential subsidence in Jefferson, Parish, La. related to peat thickness. Blank area in western part of map is undeveloped.
rates and recent explosion sites in Jefferson Parish. Lines indicating peat thickness are superimposed for reference. All the explosions are believed to have been caused by subsidence-related gas line ruptures.

Kenner, Louisiana—A Case History

Kenner, Louisiana is a thick peat area located in the western part of the metropolitan New Orleans area. The history of subsidence in Kenner is representative of what has occurred in much of the drained and developed marshland. Examination of this subsidence history should provide a guide-line for establishing the proper waiting time between drainage and construction in order to mitigate subsidence-related damage. The following case history of land subsidence was reported by Traughber, Snowden and Simmons (1978).

Early condition—Prior to 1924

Originally the areas of lower elevation in Kenner were marsh and swamp, similar to those now existing in St. Charles Parish to the west. Inasmuch as the level of Lake Pontchartrain adjacent to the Kenner area is nearly 30cm above mean sea level (MSL), it can be concluded that the original marshland was at this same elevation. The upper layers were generally very light and, in many cases, tended to float. The dry-unit weight of this material could be as little as 0.2g/cc. Drainage of this type of land results in large amounts of immediate subsidence as the unstable upper material compresses.

Beginning Development—1924 to 1949

Initial drainage pumping started in the mid 1920's, with the old New Orleans-Hammond Highway (State Highway 33) acting as a protective embankment along the shore of Lake Pontchartrain. By 1946 the crest of this load embankment had been reduced from an elevation of + 1.5m MSL to approximately + 1m MSL due to wash or subsidence. The four pumping stations in Jefferson Parish were poorly maintained and one was taken out of operation in 1932 because of a break in the foundation. The pumping primarily benefited those areas of Kenner closer to the river, and the northern areas remained swampy throughout the period of 1924 to 1949.

Development after 1949

On September 19, 1947, a hurricane struck the Lake Pontchartrain area, causing sustained flooding in the lower-lying areas of Jefferson Parish. The old New Orleans-Hammond Highway embankment was breached and overtopped. The flood damage which occurred was the impetus for construction of a new levee-protection system along the lakeshore and the Jefferson Parish-St. Charles Parish line. Improvements in the pumping capacity of the drainage system also were implemented. The levee and drainage improvements began in earnest about 1949 and were com-
completed by 1953. This provided the first opportunity for major housing construction in the northern section of Kenner. The first residential development in northern Kenner, begun in 1953-54, had unpaved shell roads. The development continued and accelerated with the construction of major thoroughfares such as Interstate Highway 10 and Veterans Highway. Improvements to existing streets and construction of new ones brought the development to its present stage.

Subsidence 1924 to 1935

As previously stated, the elevation of the original marshland in 1924 was +0.3 m MSL. A 1935 survey shows that subsidence had lowered the elevation of the area near the lakeshore, generally north of present-day 42nd Street, between sea level and +0.3 m MSL (United States Geological Survey, 1938). The 1935 survey shows the subsidence had caused an interior basin to form. This low-lying area—generally between sea level and -0.3 m MSL, acted as a temporary holding reservoir during periods of heavy rain. The area to the south of the interior basin increased in elevation toward the river.

Subsidence 1935 to 1949

In 1949 the low lands in Jefferson Parish were still swampy and supported heavy growths of wild cane, sawgrass, and other tropical and semi-tropical vegetation. Pumping was still beneficial, primarily only to those areas of Kenner nearest the river. The pumping-stations were generally poorly maintained and only 5 of the original 8 pumps were still operating. The New Orleans-Hammond Highway embankment had deteriorated or subsided so that it was inadequate for protection against even normal high tides in Lake Pontchartrain. Some measure of protection against flooding was provided by maximum subsidence areas, which served as catch basins for rain water that slowly drained by pumping. These conditions and the fact that the area near the lake was still at an elevation between sea level and +0.3 m MSL (U.S. Army, Corps of Engineers, 1948) indicate that no substantial areal subsidence occurred between the years of 1935 and 1949.

Subsidence after 1949

A survey made in 1970 by the Corps of Engineers shows the same basin-like topography that existed in 1935. The interior area was on the order of 0.3 to 0.6 m lower than the strip of high ground near the lake. However, comparison of the 1970 survey shows a general overall subsidence of approximately 1.2 m in the part of Kenner north of Interstate 10 highway. Since there apparently was no appreciable lowering of the water table or subsidence during the period 1935-49, it has to be concluded that approximately 1.2 m of subsidence occurred in that area during the 21-year period between 1949 and 1970. This has been confirmed by field measurements of areal subsidence near houses that were built at different times.

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FIG. 8. Approximate subsidence history and estimated future subsidence for Kenner, Louisiana, north of Interstate 10. Normalized for peat thickness of 2.5m.

Because of better drainage, the areas along the southernmost part of the interior basin experienced even more subsidence. Comparison of data from 1935 to 1970 indicates that there was approximately 1.5m of subsidence between those dates along the southern boundary of the interior basin. This is in an area with thick layers of peat (4.6-5.5m) overlain by thin layers of clay. There are small local areas with subsidence probably as much as 2m near canals where the drainage drawdown was greatest.

Time-Subsidence Curve - 1924 to 1978

Field measurements were taken to determine the differential subsidence which has occurred at residences built at various times since about 1949. These measurements and information on subsidence for the period 1924-49 were used to determine the approximate subsidence history for the area of Kenner north of Interstate 10 Highway (Fig. 8). The curve represents the sub-
sidence history for a location with an average peat thickness of 2.5m.

The time period from 1924 to 1935 (Fig. 8) represents the initial drainage of the area after construction of the Hammond Highway embankment. During this time the water table was lowered. At the end of this period the water table was still approximately at the ground surface, but the elevation of the ground surface was 0.5 to 0.7m lower than it was in 1924. The period between 1935 and 1949 was a time of minimum and relatively static drainage levels (Fig. 8). During this period the embankment and pumps were often in a state of disrepair, with several completely out of operation. Little subsidence occurred during this time period, and if no further improvements in drainage or levee protection had occurred, the settling would have followed a curve something like the upper dashed line in Figure 8.

The new levee and improved drainage system caused the subsidence rate to increase in 1949. Although some remedial measures were taken to improve the flood protection system after the hurricane of 1947, it was not until 1949 or 1950 that significant construction began on the levee system. This levee was essentially finished by 1952 or 1953, and the first residential development north of Interstate Highway 10 was occupied in October 1954. The real-estate developments at that time had shell roads and side ditches for surface drainage.

Increased subsidence rates occurred during the period of 1949-59 (Fig. 8). As the new pumps and the new levee system improved the drainage, there was substantial lowering of the water table. The rate of subsidence slowed toward the end of the 1950's as the water table again held fairly constant during a period of slower development. The subsidence rate would have continued to decrease as estimated by the middle dashed line in Figure 8 if no further improvements in drainage had been made.

In 1959 or 1960 construction in the area north of Interstate Highway 10 accelerated with a dramatic increase in the number of paved streets. The roof areas and paved areas greatly reduced the open ground available for absorption of rainwater so that the volume of surface runoff increased. This caused both general lowering of the water table and increased demands on the pumping system. The majority of the subsidence due to this increased development probably occurred between 1959 and the mid 1960's. Since the mid 1960's the subsidence rate has slowed, and it is now between 1.2 and 2.5cm per year. If no further changes in the water-table occurs, the rate of subsidence should continue to decrease. For this condition, the estimated future subsidence is shown by the lower dashed line extending beyond the year 1978 in Figure 8. However, if there is further lowering of the water table, there will be another period of rapid subsidence, as indicated by the steeper dashed-line curve. Therefore, any new drainage projects in the area must be carefully designed to avoid further lowering of the water table.
Summary
Now that the relationship between drainage and land subsidence is relatively well understood in the region, it is possible to predict areas that have the potential for future hazardous subsidence. Present drainage systems should be modified and future systems designed to keep subsidence-prone sediments and soils as wet as possible. Water table levels should be kept as high as possible. Thorough geological and geotechnical surveys should be done prior to further drainage projects within the Mississippi River delta plain.

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