SUBSIDENCE OF ORGANIC SOILS AND SALINITY BARRIER
DESIGN IN COASTAL ORANGE COUNTY, CALIFORNIA

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Abstract
Lenticular deposits of peat and organic sediment accumulated widely across the coastal plain of Orange County during the Holocene epoch. Dewatering of these organic sediments resulted in initial shrinkage of the materials and subsequent oxidation and decomposition. Agricultural drainage of coastal marshy lands and later extractions of ground water resulted in lowered levels of saturation. Decline in ground water levels was accompanied by localized subsidence of areas underlain by peat. Continued decline also resulted in the invasion of saline ocean waters into the coastal aquifers. Intrusion was most pronounced in the Santa Ana Gap area of Huntington Beach, and by 1964 increased chloride ion concentrations had progressed about 4 miles (6.4 km) inland from the coast.

In order to preserve the coastal ground water basin, a salinity barrier was constructed following extensive studies by the California Department of Water Resources and the Orange County Water District. The hydraulic barrier consists of a line of extraction wells near the coast and a parallel line of injection wells located farther inland. The dual concept was adopted to minimize the decline of water levels and the resulting local dewatering of organic materials, while at the same time reducing the likelihood of excessive waterlogging of the surface soils along the injection ridge. Water for the injection wells is a combination of tertiary treated waste water and de-mineralized water blended to meet public health requirements.

Introduction
Subsidence has long constituted a serious problem in the reclamation and development of peat lands in many parts of the world. The purposes of this paper are to present information on the origin, character and location of peat and to describe the nature of peat subsidence in coastal Orange County and its effect upon salinity barrier construction. The study area is shown on Figure 1.

The study included review of pertinent published and unpublished reports, collection of geologic, hydrologic, and elevation survey data, and field observation of peaty areas. Additional information was obtained through consultation with local firms and public agencies at the City, County, State and Federal level and with numerous long-time residents in the Fountain Valley area.

Nature of Peat and Organic Soils
Peat and organic soils form in water-saturated environments where incomplete decomposition occurs due to prevailing anaerobic conditions. In Orange County, environments favorable to luxuriant growth of peat-forming plants include undrained depressions, plains or river deltas, and fresh water swamps. Poor drainage is essential in the formation of peat. The elevation relationship between surface water or ground water and land surface must remain relatively constant for long periods of time if significant quantities of peat are to accumulate and be preserved. Within the coastal plain of Orange County, logs of many water wells and soil borings indicate that these conditions have long been prevalent.

In the Quaternary period, near the end of late Pleistocene time, sea level declined to about 300 feet (90 m) below its present level. During
that period, an ancient Santa Ana River eroded deep valleys across the coastal plain to the receding base level. With a subsequent rise in sea level during early Holocene time, these valleys were backfilled, first with coarse alluvial debris. Later, the rate of sea level rise decreased, and the ancestral Santa Ana River appears to have deposited finer-grained materials in the valleys or gaps. While periodic shallow marine embayments occurred in portions of the gaps, the area was generally very slightly above sea level. It was during this period that extensive deposits of peat accumulated. Resulting general geologic features are shown on Figure 2.

The geologic history of the area suggests that not only were repeated flooding, ponding and burial significant factors in accumulation of peat, but also that continued upward flow of artesian ground water from the underlying coarse alluvial materials was important. Locally, upwelling ground waters and resultant "peat springs" must have remained in a relatively constant location. Logs of several water wells show that peat deposits extend from the surface downward to the top of the coarse alluvium. According to pioneer, T. B. Talbert, springs and general swampy conditions persisted until the time of agricultural development. He states that upon his arrival in 1897, (Talbert, 1952, P. 37) "This area...was so full of peat springs and artesian wells which flowed the year around that it was quite inaccessible. It had a growth of willows, sycamore, tules, ...and other vines, grasses and shrubs that made it almost an impenetrable thicket."

Location of Peat Deposits

Delineation of peat deposits in the coastal plain was originally made from a review of all available soil boring logs, water well drillers' logs, old maps, and through personal communication with local residents. This information was updated through review of information developed by Messrs. J. Evans and R. Munson for the cooperative mapping program of the County of Orange and the California Division of Mines and Geology. The historic locations of major bodies of organic sediment are shown on Figure 2.

It is interesting to note that within approximately 1 mile (1.6 km) of the present coastline, significant quantities of peat have not been encountered. Generally, conditions are not favorable for the luxuriant growth of peat-forming plants in coastal areas which are subject to frequent incursions of saline ocean water. Prior to residential development, the coastal area was interlaced by tidal sloughs, and surface soils were encrusted with salts. If these saline conditions persisted throughout late Holocene time, it is not likely that any major peat deposits will be found near the present coastline.

Subsidence Rates

Subsidence of organic soils in the Fenland area of England was first noted in 1806 (Okey, 1918), after initial drainage of the area for agricultural uses. The famous HOLME POST, sunk solidly into clays underlying the peat at Holme Fen in 1848, is probably the oldest authenticated record of peat subsidence in existence. Measurements at that site show a lowering of the ground surface of 10 feet (3 m) in a 65-year period. Although subsidence rates were probably not constant, these records indicate an average subsidence of 1.9 inches (4.8 cm) per year.

Subsidence in the Everglades region of Florida, the Delta region of California, and an area of peat springs in Huntington Beach have been observed and noted following drainage or change in overall levels of saturation. Subsidence in these areas has been estimated to range from about 2 to slightly over 3 inches (5 to 7.6 cm) per year.
EXPLANATION

- LATE PLEISTOCENE MESA SURFACES
- AREAS HISTORICALLY UNDERLAIN BY ORGANIC SEDIMENTS
  - PROBABLE OCCURRENCE
  - 0.3 TO 3 FEET IN THICKNESS (0.15 - 1.5 m)
  - 5 TO 25 FEET IN THICKNESS (1.5 - 7.6 m)
- ZONES OF MAJOR FAULTING (DASHED WHERE APPROXIMATE, DOTTED WHERE CONCEALED)

HISTORIC LOCATION OF ORGANIC SEDIMENTS
COASTAL PLAIN OF ORANGE COUNTY, CALIFORNIA
SCALE 5000 10000 FT. 3000 M.

BASE MAP AFTER CALIF. DIV. OF MINES AND GEOLOGY REPORT 15, 1973

DECEMBER, 1976
FIGURE 2
Although no actual records of annual peat subsidence were kept in the Orange County area, it is considered that the elevations of peat land in the City of Fountain Valley were at or above prevailing ground surface prior to 1897. By 1949, elevation contours suggest subsidence averaging 10 to 14 feet (3 to 4.3 m) in areas underlain by major bodies of peat. In a few locations, up to 20 feet (6 m) of subsidence had occurred. Based upon these estimates, subsidence has averaged 2.3 to 3.2 inches (5.8 to 8.1 cm) per year.

Causes of Subsidence

The most important causes of peat subsidence include wind erosion, burning, compaction by tillage machinery, shrinkage resulting from reduction in moisture content, and decomposition and decay. Another more obvious factor is simply the cessation of peat deposition. Some peats, especially sedimentary types, probably consolidate as they are deposited. Continuous formation tends to keep pace with the consolidation. However, the supply of new material is curtailed when the cycle is interrupted by surface development.

Continuous submergence of organic soils during formation prevented or greatly retarded oxidation. A reducing environment allowed significant thickness of peat to accumulate and be preserved. Drainage of peat lands not only results in shrinkage of soils, but greatly stimulates the subsequent loss of soil mass by allowing oxidation from biochemical action. Considering past events and conditions of drainage, oxidation is considered to be the major cause of peat subsidence in the Orange County Coastal Plain.

Effect of Water Level Fluctuations on Orange County Peats

Peat soils may shrink as much as 60 percent when the moisture content is reduced to about 35 percent. From studies in other areas, it appears that with the lowering of water saturation levels, shrinkage occurs first and is followed by relatively continuous decomposition or oxidation of the dewatered organic material.

Local areas of the Orange County Coastal Plain were developed for agricultural purposes on a large scale in 1898. Springs were first drained and later drainage ditches were dug to the tidal inlets and channels. By 1901 tile drains had been installed in a major portion of the area. Personal communications with early settlers suggest that subsidence adjacent to the "peat springs" occurred almost immediately after drainage of the land had started, and that by 1915, the major part of localized subsidence throughout the area had occurred.

In an attempt to document the conclusions of long-time residents, the authors collected useful historic elevation and surface contour data. The few historic traverses for which records exist were run primarily along section line roads. As local subsidence occurred, fill was repeatedly placed on the roadbeds and no bench marks were established in these subsiding areas. A number of early elevations were obtained for the town intersection of Talbert Avenue and Bushard Street. These indicate that the intersection has remained relatively constant in elevation since 1898, at about 24 feet (7.3 m) above mean sea level.

The most valuable historic elevation data on subsidence were obtained from successive U.S.G.S. quadrangles and from surveys made for the Talbert Drainage District. For analysis, a suitable site adjacent to a known body of sedimentary and fibrous peat was selected, and all surface elevation and water level data available for this location were plotted against time. These data are shown on Figure 3. Historic water levels for the underlying alluvial materials were obtained from a composite of records of wells 5S/10W-28B1, 6S/10W-5B5 and -6L2. The initial elevation of a nearby subsurface drain is
SURFACE SUBSIDENCE AND GROUND WATER LEVELS
1895 TO 1976

Original ground surface elevation
Approximate level of subsiding surface
Ground water levels
Elevation of drain
Fill for trailer park

Site location:
Near Talbert Avenue and Bushard Street
Fountain Valley, CA.

Elevation in feet
Elevation in meters

Time in years

Figure 3
depicted by a straight line. The apparent subsidence at the location totaled 10 feet (3 m) from 1898 to 1964. In 1966, the location and surrounding area were partly backfilled for the construction of a mobile home park. However, the location has continued to subside, and by 1976, subsidence totaled about 14 feet (4.3 m). It is reasonable to assume that initial subsidence occurred relatively quickly after drainage. Thereafter, subsidence is projected on Figure 3 at an almost uniform rate until 1950.

By the mid-1920's, pumping of wells perforated in the underlying alluvium lowered pressure levels to below prevailing ground surface and the few remaining springs ceased to flow. By about 1930, pressure levels had declined to elevations below both the peat soils and the drains at the reference site.

By 1946, the soils themselves had subsided below the initial level of the subsurface drains at the reference site. At this time, a truer perspective of the influence of the major underlying aquifer began to develop. Peats continued to subside, suggesting that semiperched waters in the peats and surrounding materials were draining downward to the underlying aquifer, because the drains were locally above the zone of saturation. From 1947, the elevation of the piezometric surface in this aquifer declined rapidly, reaching levels of about 40 feet (12.2 m) below the peat surface in 1957. Starting about 1950, an increase in the rate of surface subsidence may be noted on Figure 3.

By 1964, the peat surface at the reference site had subsided 3-1/2 feet (1.07 m) below the level of adjacent subsurface drains. From 1964 to 1966, subsidence continued, but in August of that year the site was backfilled in part. From 1966 to 1976, the surface continued to subside at a somewhat accelerated rate.

Land Use

Land use in areas of the coastal plain where relatively thick organic sediments have not been removed has been undertaken locally with imagination and creativity. Some remaining wet or swampy areas have been developed as drainage channels, water hazards, wildlife refuges, architectural lagoons and fishing lakes. Dryer areas of organic soil are being used for driving ranges, golf courses, playing fields, parks and recreational areas, parking lots, mobile home parks and drive-in movies.

Sea Water Intrusion

Sea water intrusion has occurred in what is locally referred to as the Santa Ana Gap. This is the area where the Santa Ana River, during late Pleistocene time, eroded a deep channel into the older inland dipping deposits. The subsequent backfilling of this channel with coarse-grained deposits created a permeable aquifer in contact with the ocean which allows the landward movement of sea water if the water levels in the basin fall below sea level. The Talbert aquifer, as this Holocene age deposit is named, is approximately 3 miles (4.8 km) wide. The relationship of the Talbert aquifer and the older aquifers which are subject to intrusion is shown in the cross section, Figure 4. The Newport-Inglewood fault system extends along to the coastline and acts as a barrier to saline intrusion in all aquifers except the Talbert.

Historically, the area had a high piezometric surface with many springs and flowing artesian wells. Subsequent development and increased use of well water throughout the ground water basin lowered the piezometric surface to such an extent that sea water intrusion occurred and, by 1964, extended inland approximately 4 miles (6.4 km) from the coast. This saline intrusion posed a serious threat to the quality of the water in the remainder of the basin. The ground water basin underlies an area of approximately 200,000 acres (81,000 hectares) and at its deepest point, there is fresh water to a
depth in excess of 3,000 feet (915 m). The water in storage in the basin has been estimated to be as much as 40 million acre-feet (4.93 million hectare meters) (DWR, 1967). The annual pumping draft on the basin is approximately 225,000 acre-feet (27,743 hectare meters).

Detailed information regarding the subsurface geology and hydrology of the area was developed in several studies performed by the State of California Department of Water Resources. This information was used as a basis for the design of the barrier project which is being implemented by the Orange County Water District.

Salinity Barriers

The design of hydraulic barriers to stem the invasion of saline ocean waters in the coastal plain has been modified to a significant degree because of the occurrence of sensitive organic sediments. For example, a pumping trough barrier requires lowering of levels to elevations below inland operational water levels. Organic materials could then be dewatered, shrink, and become compressed. Subsequently, a massive reduction in volume would occur as the peats oxidize.

Because of their mode of origin, peat deposits are moderately permeable. The design of a pressure recharge barrier could entail raising ground water levels to elevations higher than ground surface. This action could result in upward leakage through the organic materials, and the local re-establishment of historic springs and swampy areas.

A combined injection-extraction barrier facility includes some of the advantages, but not the major disadvantages, of either system acting alone. For example, if operation levels at the injection ridge portion were maintained at about sea level, and extraction trough levels at about 5 feet (1.5 m) below sea level, a seaward gradient could be maintained, and the adverse effects of both peat subsidence and water-logging would be minimized.

Because of uncertainties regarding the future availability of imported water for injection in the barrier, and the close proximity of a source of secondary treated waste water, the Orange County Water District undertook an investigation to determine the feasibility of using reclaimed waste water for injection. During the period 1966 to 1970, pilot studies were carried out to investigate the various parameters necessary for the design of the barrier project. The pilot project included a small-scale water treatment plant, 3 injection wells and 12 observation wells. During this study, various water treatment methods were evaluated to determine the method most suitable for the available waste water. Treated waste water was injected in the 3 wells in order to explore the required well spacing and the necessary rates of injection for various conditions of basin overdraft.

The barrier project as finally designed consists of 7 extraction wells, 23 injection wells, a water treatment plant and a network of 29 observation wells for monitoring ground water conditions and the effects of injection.

Injection Wells

The alignment of the injection wells is along Ellis Avenue which coincides with the front of intruded saline water (Figure 5). The wells are designed to inject into each of the 4 aquifers which are subject to saline intrusion. Because of differences in aquifer transmissivity and the effects of local ground water extraction, it was considered desirable to be able to control the injection rate into each aquifer separately. In order to accomplish this, each injection site consists of up to 4 separate casings, each perforated in a different aquifer and controlled individually at the surface.

To construct the wells, a 30-inch (0.76 m) diameter hole was drilled to the required depth, using the reverse rotary drilling method. A 6-inch
Figure 5

- Observation wells
- Injection wells
- Extraction wells

T Treatmen Plant Site

PACIFIC OCEAN

TALBERT AQUIFER

TALBERT AVE.

ELLIS AVE.

GARFIELD AVE.

WARD ST.

EUCALYPTUS

SANTA ANA RIVER

BEACH BLVD.

NEWPORT INGLEWOOD

MAGNOLIA AVE.

ATLANTA AVE.

HAMPTON AVE.

FLOOD FAULT

BROOKHURST ST.

VICTORIA ST.

PACIFIC COAST HIGHWAY

SANTANA FREEWAY

SAN DIEGO
(15.2 cm) diameter, pre-perforated, mild stainless steel casing was installed for each aquifer. After installation of the casings, gravel pack was emplaced adjacent to each aquifer and a cement grout plug was placed in the clay strata between aquifers for hydraulic separation. Figure 6 is a diagram showing a typical 4-casing installation. For clarity, the casings are shown side by side; in practice they are arranged in a square.

There are 23 injection well sites spaced approximately 600 feet (183 m) apart and located in the street right-of-way on Ellis Avenue. Because the wells had to be located in the street or sidewalks, it was necessary to enclose all the surface facilities in underground vaults. Each well casing has a control valve, a pressure gage and a flow measuring device. The pressure and flow rate is telemetered to a computer in the central control building at the treatment plant site. The computer can be programmed to print out the flow and pressure of each casing as often as desired or on demand by the plant operator. The data collection is done by telemetry but control of the flow rate is done manually.

Water Supply

The supply water for the injection barrier is tertiary treated waste water. Secondary treated wastewater that would normally be discharged through the ocean outfall sewer is obtained from the Sanitation Districts of Orange County and given tertiary treatment and demineralization to produce a product water that meets the drinking water standards of the Department of Public Health. The tertiary treatment consists of lime flocculation and sedimentation, ammonia stripping, recarbonation, sand filtration, carbon adsorption, and chlorination. After this treatment, the water meets all requirements except for total dissolved solids (TDS). In order to meet the TDS requirements of 500 mg/l, the water must be blended in the proper proportion with a low TDS water. The low TDS water will be provided by a 5 million gallon per day (18,900 cm per day) reverse osmosis plant, now under construction, which will take a portion of the tertiary treated water and reduce the dissolved solids content to approximately 100 mg/l. This demineralized water will be blended with the tertiary treated water to provide a product water of the required quality. The quantity of water required, based on the pilot study calculations, could vary from 5 million to 30 million gallons (18.9 to 113.6 million liters) per day depending on the condition of the basin overdraft. The capacity of the present treatment plant is approximately 15 million gallons (56,800 cm) per day.

Extraction Wells

The 7 extraction wells are located in a line roughly parallel to the coast and seaward of the areas where the Talbert aquifer is in hydraulic continuity with the older, landward dipping aquifers. These wells are conventional gravel-packed, 10-inch (25.4 cm) diameter casings, perforated in the Talbert aquifer, and equipped with deep well turbine pumps. Pumping rates can be controlled up to a maximum of approximately 1,000 gpm (63 1/sec). The saline water pumped from these wells is wasted to nearby flood control channels which drain to the ocean.

Observation Wells

There are approximately 30 observation wells in the area which are used to monitor ground water conditions. Fifteen of these wells are intended to be used for monitoring the effects of injection in each of the separate aquifers. The design of these wells is similar to the injection wells with a separate casing installed for each aquifer. Instead of stainless steel, the casings are 4-inch (10.2 cm) diameter plastic pipe.
Operations

Construction has been completed and the treatment plant is now operating full time at a reduced rate of production. Before full scale operations begin, water will be injected at each well site individually and the effects will be monitored at the observation wells. The data from this test procedure will be used to determine the injection characteristics of each well casing and to evaluate any variations in aquifer transmissivities along the barrier. Full scale operations are scheduled to begin in March of 1977.

References

Okey, C. W., 1918, "The Subsidence of Muck and Peat Soils in Louisiana and Florida", Transactions of the American Society of Civil Engineers, v. 82.