Experience with Development of Peat Deposits at Walt Disney World, Florida

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ABSTRACT

Considerable experience was gained with the development of sites underlain with peat and highly organic soils at Walt Disney World in central Florida. The most straightforward approach was to totally excavate the organics and replace them with sand fill. The excavation techniques and equipment used depended on the total depth of organics, the size of the area to be excavated, and the seasonal groundwater conditions. Various surcharging techniques were used to stabilize the peat before construction. Several specialized approaches were used successfully: (a) A portion of a major lagoon was developed by compressing a thick organic profile by surcharging. Vertical compressions of up to 15 ft (3.0 to 4.6 m) were achieved, thus avoiding the need for significant excavation and disposal. (b) A controlled surcharge program was used to develop over 3,000 linear ft (0.9 km) of a major four-lane access road over an organic profile extending to depths of 10 to 14 ft (3.0 to 12.2 m). Surcharging was found to stabilize the peat by removing primary consolidation and reducing the rate of secondary compression. (c) A section of an elevated monorail system in a deep organic area was developed in a phased sequence of surcharging, partial removal of surcharge, driving piles, and additional surcharge removal. (d) A finite-element program was used to assess the general vertical and horizontal displacement pattern within a sand fill extending partly over highly compressible organic soils. The purpose of this study was to evaluate the distance from the edge of the soft ground area where a structure could be safely supported in the sand fill.

Walt Disney World is located in central Florida about 15 miles (24 km) south of Orlando (Figure 1). The Disney World property contains approximately 42 square miles (109 km²) of land. Before development, much of the property was covered with dense vegetation and there were large areas that were swampy and underlain by peat and highly organic soils.

The initial development of the property began with the construction of the Magic Kingdom in the late 1960s. A site was selected where the near-surface soils consisted primarily of sands, which minimized grading and allowed shallow foundations to be used for support. However, it was still necessary to develop some of the peat areas.

The peat areas encountered during initial construction generally contained less than 10 ft (3.0 m) of organics. For the most part, the organics were excavated and replaced with sand fill. However, this

FIGURE 1 Location map.

straightforward approach to the development of peat sites was not always possible during the recent development of the 500-acre (202-ha) Experimental Prototype Community of Tomorrow (EPCOT) site, for which field investigations began in 1978.

The majority of the EPCOT site is underlain from the surface by about 40 ft (12.2 m) of medium dense to dense sand. However, the site is bordered by heavily vegetated, low-lying ground and there was a large low-lying area covering approximately 50 acres (20 ha) located near the center of the site. In these low areas, peat and organic soils were typically found to extend from the surface to depths of 5 to 20 ft (1.5 to 6.1 m); in some areas the depth of organics exceeded 60 ft (18.3 m). The nature of the development planned and the location and the extent of the peat deposits required considering alternatives to the total excavation and replacement techniques used previously. The selection of an alternative depended on time and economic constraints as well as engineering judgment, including an assessment of the uncertainties and their potential impact on scheduling, initial costs, and projected maintenance costs.

INVESTIGATION OF PEAT AREAS

The identification of peat areas was initially made on the basis of a visual inspection of the site. Peat was generally found in lower ground areas, containing mature bay, black gum, cypress, and some pine trees, with a thick undergrowth of low brush around the perimeter. There was also often evidence of standing water. Because Florida terrain is typically flat, the term "lower ground" meant that the ground surface was only 1 to 4 ft (0.3 to 1.2 m) lower in elevation than the surrounding "higher ground."

A preliminary estimate of the lateral extent of the peat was made on the basis of soil maps from the Soil Conservation Service, U.S. Department of Agriculture, and a review of aerial photographs and topographic maps. The photographs, including infrared photographs, were examined for vegetation patterns or other surficial features that might define changes in subsurface conditions. Topographic maps identified the limits of the lower ground areas. Sometimes, the lower ground areas or the vegetation patterns were nearly circular in plan, suggesting a relationship with past sinkhole development (collapses of cavities within the underlying limestone formation).

Additional preliminary information on the peat areas was developed using a hand-probing program. The probe used consisted of 1/2-in. (1.3-cm) diameter steel rods that were carried in 5- to 10-ft (1.5- to 3.0-m) sections. The probes were typically performed throughout the area of interest on a grid pattern using 50- to 100-ft (15.2- to 30.5-m) spacing. The rods could be pushed by hand through organic profiles approximately 20 ft (6.1 m) deep without encountering much resistance. By using wrenches or a 40-lb (18-kg) drop hammer, the rods could be advanced to greater depths [in one instance in excess of 70 ft (21.3 m)]. It was not uncommon to find peats interbedded with sand layers; therefore, the probing did not stop at the first sign of an increase in resistance. It is recognized that conclusions based on such probing are fairly subjective. However, if probing is done carefully, useful information can be developed to help in planning a more detailed drilling and sampling program. For example, the results of the probing were used to develop a rough contour map of organic thickness.

Conventional truck-mounted drilling equipment could not be used in the peat areas. Therefore, the boring and sampling program required the use of a track- or skid-mounted rig. The skid rig was moved through the area by clearing a path through the vegetation and using the remaining trees to winch the rig from location to location. Drilling was done either by rotary-wash or chop-and-wash techniques. Water for the drilling operation was obtained from the near-surface water table.

The rigs used for this study were capable of drilling to depths of 230 ft (61 to 70 m). Most of the borings were advanced into the underlying limestone formation to evaluate its integrity and check for the presence of large cavities. The borings were advanced at least 15 to 20 ft (4.6 to 6.1 m) below the last organic layer and into competent material.

Samples of the peat and organic soils were obtained using a variety of sampling techniques, including a split-barrel sampler with Shelby tube extension, and a piston sampler. It was extremely difficult to obtain good samples within the upper 5 ft (1.5 m) of the profile due to the presence of abundant coarse roots and the extensive root systems in this zone.

NATURE OF PEAT

The peat sites primarily contained mature tree growth that would be classified as coverage type A, after Radforth (1). The ground surface was underlain by a "rootmat" of living and partially decomposed root systems. The rootmat layer was typically 1 to 5 ft (0.3 to 1.5 m) thick and contained very little, if any, soil material. These interwoven root systems provided a natural reinforcement that could support light vehicles.

Below the rootmat, the peat ranged from "stringy" and "spongy," to highly decomposed vegetation matter, to material that contained equal amounts of organics and mineral soils. The organics were usually in the form of very fine root fibers with a diameter of less than 1/32 to 1/64 in. (0.8 to 0.4 mm). Below a depth of about 5 ft (1.5 m), the fiber structure was usually highly decomposed. Some samples showed no evidence of fibers. These lower peats would generally fall into categories 1 to 5, amorphous granular, of the Radforth classification of peat structure (1), with most samples in categories 4 and 5.

The typical ranges in the physical properties of the peat are

Property	Typical Range of Test Results
Wet density	60 to 80 pcf (1.0 to 1.3 g/cm³)
Moisture content	140 to 1200 percent (based on dry density)
Dry density	4 to 32 pcf (0.06 to 0.5 g/cm³)
Organic content	50 to 95 percent (based on dry weight)
Ash content	5 to 50 percent (based on dry weight)
Shear strength	< 100 to 400 psf (< 4.8 to 18.6 kPa)

It was not unusual for the organics to be interbedded with loose sands. In addition, soft to medium-stiff organic layers were sometimes encountered below stiffer layers. It is believed that the stiffer layers had consolidated through desiccation during fluctuations in the groundwater level.

Laboratory consolidation tests showed that the peat was highly compressible, with samples consolidating from one-fourth to one-half their original thickness under moderate loads. The test samples were first consolidated under a nominal load of 100 to 200 psf (4.8 to 9.6 kPa), which simulated placement of a thin working platform of fill over the peat and also tended to remove some of the disturbance caused during sampling. The samples were then loaded to anticipated field levels.

Typical summary plots of primary consolidation (expressed as sample strain) versus the log of the applied load, and the coefficient of secondary compression (C_S) versus the log of the applied load are present in Figures 2 and 3, respectively. Note that the results in Figure 2 show an increase in sample stiffness when samples from progressively deeper strata are compared.

EXCAVATION TECHNIQUES

General

The most positive approach to the development of a peat deposit is complete removal of the organics by excavation and replacement with sand fill. The techniques used to excavate the peat depend primarily on the total depth of the organics, the size of the area to be excavated, and the seasonal groundwater conditions.

Front-End Loaders

During the dry season, the peat and organic soils could be excavated to depths of about 6 ft (1.8 m) using front-end loaders working from the underlying natural sands. The use of front-end loaders allowed good control for cleaning of the bottom of the excavation to remove all of the organics. However, if

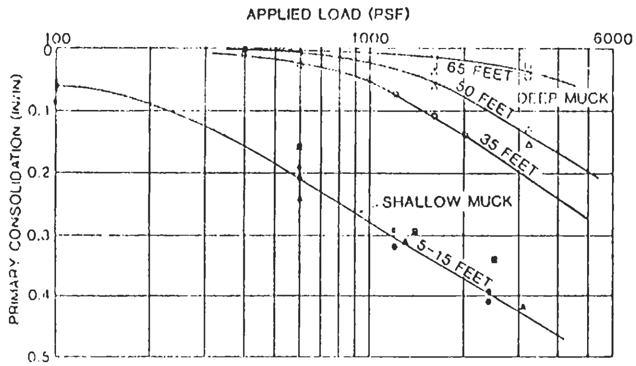

FIGURE 2 Primary consolidation versus log of applied load.

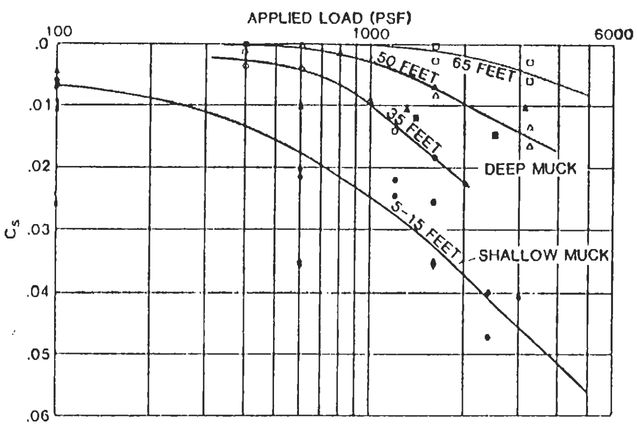

FIGURE 3 Coefficient of secondary compression versus log of applied load.

the excavation became wet, the use of front-end loaders generally had to be discontinued because of poor trafficability.

Backhoes

Backhoes were used for excavation of organic materials that were known to be wet. The water flowing into the excavation was diverted from the face of the cut to one or more sumps. These sumps were simply holes dug below the level of the excavation. Pumps were placed in the sumps to discharge the water away from the work area. The intakes on the pumps were protected by strainers. The strainers were often clogged by fiberous and woodier portions of the peat, and it was necessary to continuously switch sumps or pumps to maintain the dewatering operation.

In the usual backhoe operation, the machine cut a strip as far out as it could reach, working parallel to the edge of the peat deposit. All the organic material was removed down to clean sand. The excavated material was loaded directly into scrapers or trucks for disposal. As the backhoe moved, the excavated zone was filled with sand and compacted.

If during the excavation operations the inflow of groundwater became large enough that the bottom of the excavation could not be visually inspected, the operations had to be stopped until the excavation could be pumped dry and the bottom observed. During this stage of the operation, the contractor often used a backhoe to bail portions of the excavation to speed the dewatering operation. Ideally, if the sand under the organics could be dewatered by deep wells or properly placed well points, a more efficient demucking operation could be conducted.

Draglines

For larger areas and deeper excavations, a dragline was used. However, the use of draglines caused a sloppy operation, because of the overflow of material from the bucket and the highly disturbed state of the excavated organics. The water at the face of the excavation could be controlled with difficulty by means of sumps and temporary ditches. Removing the water allowed the bottom of the excavation to be cleaned by bulldozers.

As did the backhoes, the dragline excavated a strip as far out as it could reach and each strip was then filled with compacted sand. Because of the method of dragline operation, the leading edge of the backfilled sand adjacent to where the equipment sat was partly removed and wasted when excavating the next organic strip.

The excavated muck was wet and sloppy and was often placed behind the dragline and allowed to dry before being hauled to the disposal area. The working of draglines, the cleaning of the bottom of the excavation, the fill placement, the dewatering, the shifting of pumps, and the positioning of the scrapers or trucks being filled required constant direction. However, when working well, the choreography of a dragline demucking operation was truly impressive.

Displacement

Another means of removing peat was by displacement. In this method of removal, a bulldozer was used to push the mud and muck out, and the area behind the bulldozer was filled with compacted sand. Soft organic materials on the order of 5 ft (1.5 m) deep could be removed by this method; if done carefully, deeper displacement was also possible.

It was necessary to keep the working pad low, no higher than 3 or 4 ft (0.9 to 1.2 m) above the bottom of the excavation, and to push down and out with the bulldozer blade. A sand berm carried in front of the blade formed a temporary dike for the water and displaced organic material. If the sand berm was allowed to get too high, it flowed over and covered the muck being removed. It was also necessary in this operation to be careful that there were no reentrant angles to trap the mud wave being pushed in front. Occasionally, it was necessary to excavate the contaminated sand berm or mud wave ahead of the bulldozer to prevent a buildup of this material from flowing back into the excavation or onto the newly placed fill.

Dredge

If the excavation area is large enough, the use of a small hydraulic dredge may be justified. In this operation, the area was cleared and grubbed using light draglines with 1-yd^3 (0.8-m^3) buckets operating on mats. The draglines were equipped with an L-shaped clearing bucket, which was used to windrow the cut trees and grub the surface material and then work the spoil pile to the edge of the peat deposit, where it was loaded into trucks or scrapers by front-end loaders and taken to the disposal area.

The dredge was equipped with a revolving cutter head that could slice through any roots and smaller stumps. When the cutter head became clogged, it was cleaned by reversing. The bottom of the hydraulically dredged area was extremely irregular. The dredge operator could tell when he was no longer pumping organics and was excavating sand by the increase in voltage required and the smoother pumping action. Because the dredging occurred under the water surface, it had to be controlled by soundings and sampled by hand probes. Redredging of missed areas was often required. When dredging an enclosed area, it was necessary to have a makeup water supply to keep the dredge floating and to produce a slurry of organic material that could then be pumped to the selected disposal area. Disposal can be a problem, particularly because of state and federal environmental regulations covering handling of such materials and disposal sites.

SURCHARGING TECHNIQUES

Creation of a Major Lagoon

A central feature of the EPCOT project is a large man-made lagoon that covers approximately 35 acres (14 ha). A large portion of the lagoon falls within the limits of a major peat area. The location of the organic area with respect to the lagoon is shown in Figure 4. To aid in interpreting the depth of the organic materials present throughout this area, a computer program entitled Surface Approximation and Contour Mapping (SACM) was used. This program can approximate any surface through irregularly distributed points using a weighted least-square fit. Information from borings and hand probes was used to develop the isopachs of organic thickness shown in Figure 4. As shown, a large portion of the area planned for the lagoon was underlain by more than 30 ft (9.1 m) of organics.

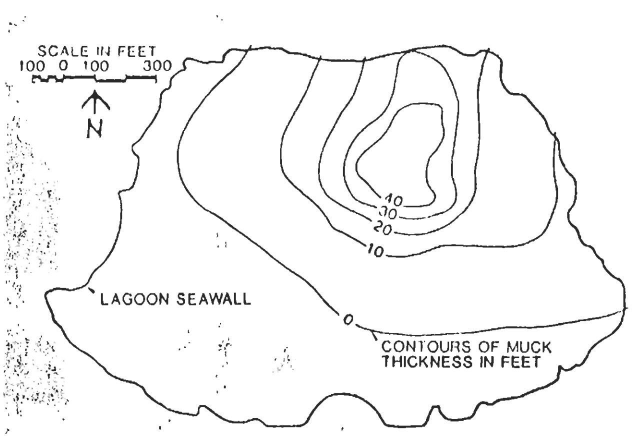

FIGURE 4 Lagoon site plan.

Because of the depth of the organics, it was not considered economical or practical to excavate completely. However, due to the high compressibility of the material, an alternative involving complete excavation of some areas and surcharging of the remainder was used to develop the planned grades within the lagoon. The concept was to contain the perimeter of the organics and then uniformly load the center to compress the surface of the peat below the planned lagoon bottom.

The original surface of the organics was at elevation +94 ft. The planned bottom of the lagoon was at elevation +84 ft. A 3-ft (0.9-m) layer of sand was planned over the bottom of the lagoon to act as a filter over the organics left in place. On this basis, the surface of the organics was required to be compressed from elevation +94 ft down to about elevation +81 ft, or about 13 ft (4.0 m) vertically (Figure 5).

In planning the construction sequence, it was necessary to consider the stability of the soft organics before they were consolidated by the surcharge. The surcharging had to be done carefully without creating unbalanced loadings on the surface because of the risk of generating mud waves. The construction approach used is shown in Figure 6. The first stage consisted of excavating a "collar" around the perimeter of the area and filling it with sand to help maintain stability by confining the peat. The organics were removed in the collar area either by dragline or by dredging to a point where the bottom of the muck was about 15 ft (4.6 m) deep. The face of the muck was cut at a slope of approximately 3 horizontal to 1 vertical. The collar excavation was then backfilled with sand. This backfilling had to be done carefully because the weight of the sand fill against the 3-to-1 muck slope could cause a heaving-type failure. However, localized heaving did not represent a serious problem because of the high-surcharge fill subsequently placed in the area.

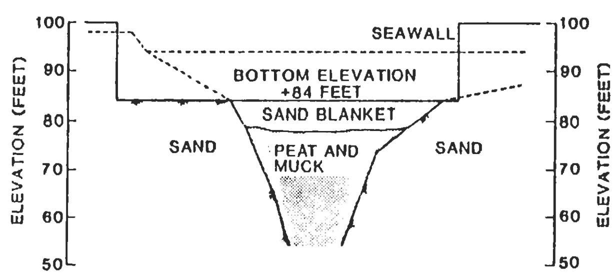

FIGURE 5 Proposed final grading.

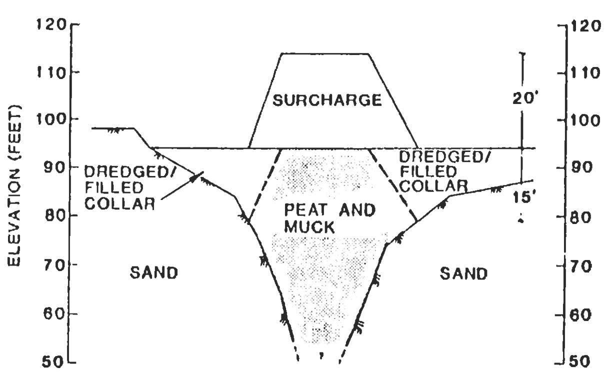

FIGURE 6 Construction phase.

The majority of the muck removal in the collar area was accomplished using a 16-in. (40.6-cm) cutter-head dredge. The dredged muck was pumped through pipes to disposal in excavations that had been developed as borrow pits about 1 mile (1.6 km) south of the project. The borrow pits were developed as a series of cells that also served as sedimentation basins for the dredge effluent. Makeup water for the dredging operations was repumped from the borrow pits, from a point at the opposite end from the discharge line, thus forming a closed-loop system.

Before surcharging the remaining peat area, large trees and brush were removed, but the surface rootmat was left undisturbed to serve as a reinforcing layer to support the surcharge soils and minimize the tendency for minor instability problems. The initial thickness of sand fill was placed hydraulically by dredge, using sands coming from the other portions of the lagoon excavation. This initial fill was placed uniformly over the peat surface in layers no more than 2 to 3 ft (0.6 to 0.9 m) thick. Small dozers were then used to place a dike over the collar area to contain the next layer of dredged sand.

After the initial layer of fill was placed over the entire area, settlement plates were installed to monitor the vertical compressions. The settlement plates consisted of 2-ft (0.6-m) square steel base plates with 1-in. (2.5-cm) diameter riser pipes. Additional fill was then placed over the area using very flat side slopes with no layer more than 2 ft (0.6 m) thick. After completing the third lift, conventional earthmoving equipment was used to place the remainder of the surcharge. The settlement pipes were raised by adding additional pipe sections as the surface of the fill increased. The settlement pipes were surveyed daily during placement of the surcharge to monitor potential instability problems. As the surcharge reached its design height, the monitoring was performed less frequently. The total surcharge placed over the peat was approximately 20 to 24 ft (6.1 to 7.3 m) thick.

Typical settlement curves observed during the surcharging are shown in Figure 7. The surcharge was placed over a 2-month period, and the full surcharge remained in place for a period of 4 to 8 months. During the surcharge program, the surface of the peat was observed to compress vertically as much as 15 ft (4.6 m). After the required compression occurred, the surcharge was removed, leaving about a 3-ft (0.9-m) blanket of sand overlying the compressed peat. As the surcharge was removed, the observed rebound was only a few inches.

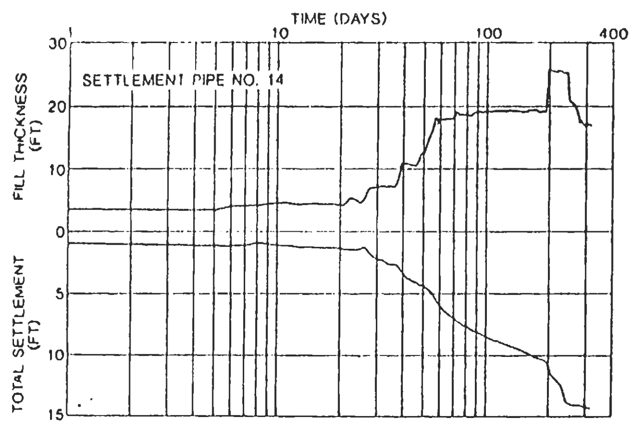

FIGURE 7 Typical settlement plots, lagoon area.

During the course of the program, portions of the surcharge were approved for removal when sufficient compression was achieved. To speed consolidation of other areas, some portions of the released surcharge material were added to other areas to create additional load. Ultimately, the surcharge material was used as fill in other portions of the project.

Overall, the surcharging program was a success. With the exception of two localized areas, the entire organic surface was compressed to the desired elevation. These localized areas required excavation of a few feet of organics and replacement with sand fill. An important advantage of the surcharging was that it avoided significant problems with excavation and disposal.

A similar concurrent program was used to create a smaller pond located to the north. The pond bottom was developed using a surcharge of 10 to 12 ft (3.0 to 3.7 m) to accomplish vertical compressions of 7 to 8 ft (2.1 to 2.4 m).

Roadway Embankment Surcharging

More than 3,000 linear feet (0.9 km) of a major four-lane access road and a large parking area were planned in areas underlain to depths of 10 to 40 ft (3.0 to 12.2 m) with peat and highly organic soils. The construction alternatives were (a) total removal of the organic material and replacement with compacted fill, (b) partial excavation and replacement, or (c) building directly on the organics following a controlled surcharging program.

The disadvantages of both total and partial removal were the cost and technical difficulties of excavation, the quantity of compacted backfill required, and the problems associated with disposal of large quantities of organic spoil. Particular problems were associated with partial muck removal, because, when the upper rootmat layer was removed, the remaining peats were particularly sensitive and the controlled placement of fill soils directly on this disturbed surface would have been extremely difficult.

The use of surcharging, or preloading, techniques to stabilize peat deposits is not unique, and surcharging has been done with varying measures of success (2-5). If done carefully, surcharging can remove the expected large primary consolidations and reduce the magnitude of long-term, secondary compressions.

The depth beyond which surcharging becomes economically attractive compared with full muck removal and replacement depends on the size of the area involved, disposal problems, and the construction time available. From a practical construction standpoint, at muck excavation depths in excess of 5 to 10 ft (1.5 to 3.0 m), the types of required excavation equipment change as do the difficulties associated with dewatering. On the basis of all factors involved for this project, it was believed that 5 ft (1.5 m) was a practical limit for complete muck removal.

The placement of an embankment, or strip surcharge, is more difficult to control than the areal surcharges discussed previously, because of the absence of confinement along the edges of the embankment and the potential for lateral squeezing of the organics at depth. Also, the rate of loading of subsequent lifts must be controlled so that the increase in shear strength that comes with consolidation takes place before the next load increment is placed.

The embankment surcharge program started with the complete excavation of organic soils to the 5-ft (1.5-m) depth contour and replacement with sand fill. In the area to be surcharged, the entire right-of-way was cleared; however, no grubbing was performed and the rootmat was left intact. Trees and brush were cut to a height about 1 ft (0.3 m) above the rootmat and removed. The initial layer of fill placed over the rootmat was pushed out using light dozers, such as a D-3 or D-5 Caterpillar tractor with wide tracks, to avoid creating a mudwave. This initial fill layer, designed to be not more than 3 ft (0.9 m) thick, was placed across the entire right-of-way. The front of the layer was kept at least 40 ft (12.2 m) ahead of the following layer. No grade changes of more than 18 in. (45.7 cm) in height were allowed to occur on this first lift. The second layer of fill was about 2 ft (0.6 m) thick and was spread over the first layer with equipment not heavier than a D-6 Caterpillar tractor. Scrapers were allowed to operate on the second layer provided excessive rutting was not observed.

The rate of loading of the peat was carefully controlled. Rough estimates of the initial critical embankment height that could be supported by the peat were based on experience (2,4,5). In general, after placement of the second lift of fill, a limiting loading rate of 1 to 1.5 ft (0.3 to 0.5 m) of fill per week was used. This rate was derived during the surcharge program using settlement plate data and observations of general stability. In addition, two test sections were developed where inclinometer casings and pore pressure transducers were installed to help monitor stability. As the surcharge approached its final height, no fill was added unless the daily settlement rate was less than 1/4 in. (0.6 cm).

The final grades planned for the roadway were typically 5 to 9 ft (1.5 to 2.7 m) above the original grades in the area. In general, the height of the surcharge was extended to an elevation 5 to 7 ft (1.5 to 2.1 m) above the planned final grade for the roadway surface. When placing the surcharge fill, side slopes of 3 horizontal to 1 vertical or flatter were maintained. Final roadway slopes were trimmed somewhat flatter, between 5:1 and 6:1, to allow for maintenance mowing of the grass.

Preliminary estimates of settlements and settlement time rates anticipated under the surcharge loads were based on laboratory consolidation tests using the following equations after MacFarlane (2):

$$S_o\text{field} = (H_o\text{ field} \times S_o\text{ lab})/(H_o\text{ lab}) \tag{1}$$

$$t_o\text{field} = [(H_o\text{field})^i \times t_o\text{lab}]/(H_o\text{ lab})^i \tag{2}$$

where

- S_o = settlement due to primary consolidation,
- H_o = initial thickness,
- t_o = time required to complete S_o, and
- i = exponential parameter, generally 1.5 to 2.0.

Secondary compression was estimated by the use of the following equation (2):

$$S_s = C_s H \log_{10} t/t_o \tag{3}$$

where

- S_s = magnitude of secondary compression;
- C_s = coefficient of secondary compression; slope of settlement-log time plot divided by the thickness of the sample at the completion of primary consolidation;
- t = field time considered; and
- H = thickness of peat at t_o.

Prediction of the magnitude of field settlements and settlement time rates for peat deposits is difficult at best. Some minimum level of field investigation, together with laboratory testing, is required to make the initial judgment as to whether surcharging is practical from a scheduling standpoint and is likely to result in an acceptable condition from a long-term performance standpoint. However, due to the uniqueness and horizontal and vertical variability of each peat deposit, no amount of laboratory testing can substitute for empirically developed data. Therefore, a settlement monitoring program should be included as part of any surcharge program in order to evaluate the positive effects of the surcharging, to provide data for judging when the surcharge can be removed, and to predict long-term performance. These field data will also allow empirical adjustment of the predictions made from laboratory tests and thus improve available analytic approaches.

For this project, settlement pipes were installed at 100-ft (30.5-m) spacing along each major section of the surcharge. The pipes were installed after placing the initial layer of fill. The contractor was responsible for protecting the pipes and there was a specific penalty for any settlement pipe destroyed and not replaced promptly.

A subsurface profile along a surcharged road section is shown schematically in Figure 8, and a typical settlement curve observed during the surcharge period is shown in Figure 9. In general, the areas surcharged were underlain by 10 to 14 ft (3.0 to 3.7 m) of organic material. Overall, the organic profile was compressed about 5 to 6 ft (1.5 to 1.8 m) under a total fill and surcharge load of about 1,500 psf (72 kPa). This settlement represents about 35 to 45 percent of the initial thickness of the peat layer. The observed settlement is generally in good agreement with the prediction obtained using Figure 2. Approximately 2 ft (0.60 m) of the settlement took place during placement of the initial 3-ft (0.9-m) layer of fill and is believed to have resulted primarily from compression of the open-gapped rootmat layer. Primary settlements occurred during a 40- to 90-day period.

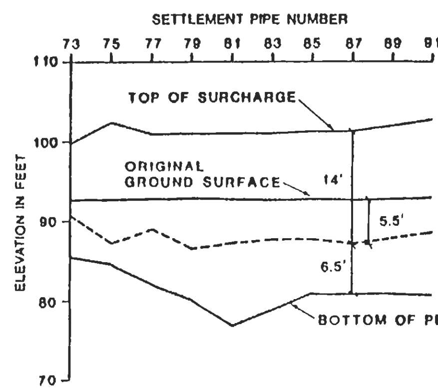

FIGURE 8 Schematic profile along surcharged road section.

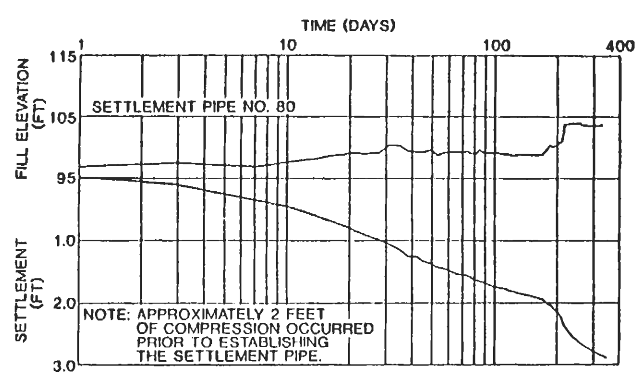

FIGURE 9 Typical settlement plot along surcharged roadway.

Approximately 4 ft (1.2 m) of surcharge were removed from the area to establish final planned grades after primary consolidation had been completed; this represented approximately 30 percent of the total fill plus surcharge load that had been applied. In the 1.5 to 2 years following removal of the various surcharges, the secondary compression has typically been measured as approximately 0.5 to 1.0 in. (1.3 to 2.5 cm). To date, the measured values of secondary compression are about one-half the values obtained using Equation 3 and Figure 3, which indicates another positive effect of the surcharging. This reduction in the rate of secondary compression after surcharging was also observed by Samson and LaRochelle (4) for a similar level of loading.

The laboratory work of Dhowian and Edil (6) suggests that loaded organic deposits may undergo a tertiary settlement phase that occurs after the secondary phase and at an accelerated rate compared with the settlement rate during the secondary phase. This tertiary phase may begin several years after completion of primary consolidation. However, the tertiary settlement phase apparently has not been observed in the field and may be a laboratory phenomenon. Periodic settlement readings are still being taken to record the performance of the surcharged areas on this project. These data will provide information on the long-term settlement rates, including the possibility of tertiary settlements.

OTHER CONSTRUCTION ON PRECOMPRESSED MUCK

A section of an elevated monorail system crosses an area underlain with a thick organic profile. Within this area, the monorail is supported on long piles driven to refusal into the underlying limestone formation. Before installing the foundations, a 10- to 12-ft (3.0- to 3.7-m) high surcharge was placed over the organics to compress the surface of the peat below the elevation of the bottom of a pond planned in this area. After the required vertical compression was achieved, approximately one-half of the surcharge soils were removed along the monorail alignment. The remaining fill was left over the compressed peat to serve as a working platform to support the construction and pile-driving equipment.

Following driving of the piles and installation of the pier columns and the beamway, all but a 2-ft (0.6-m) blanket of sand was removed from the area. The pond was then filled with water. Because the organics had been surcharged to a fairly high level, the 2-ft (0.6-m) blanket of sand left in place did not represent a load sufficient to cause any further movements within the peat profile. Therefore, the final condition was similar to having the pile-supported monorail piers installed across an undisturbed peat deposit.

During installation of the piers, inclinometer casings were installed to monitor any horizontal displacements occurring near the piers. In addition, settlement plates installed as part of the surcharging program were used to continue to monitor any vertical settlements in the area. After the pier columns were installed, survey monitoring continued on both the vertical and the horizontal position of each of the piers. This monitoring verified that there were no movements of any of the piers.

FINITE-ELEMENT ANALYSIS OF DISPLACEMENT PATTERNS IN A SAND FILL ON SOFT GROUND

As mentioned earlier, it is difficult to predict with much confidence the field performance of peat on the basis of laboratory test results. The best predictions are based on empirical correlations derived from actual field observations. However, sophisticated numerical techniques can still provide useful information and can be used to advantage.

A finite-element analysis was undertaken to evaluate the displacement pattern developed within a sand fill resting partly on an organic profile. The purpose of the analysis was to evaluate the distance from the edge of the soft ground where a structure could be safely supported on the sand fill. The generalized subsurface profile considered in the study area is shown in Figure 10. The sand fill was modeled using an incremental nonlinear elastic finite-element program. The details of the analysis have been described by Roth et al. (7). The lower boundary of the model was taken as the contact between the sand fill and the organics. In the study, the lower boundary was incrementally dropped, simulating settlement within the soft soils.

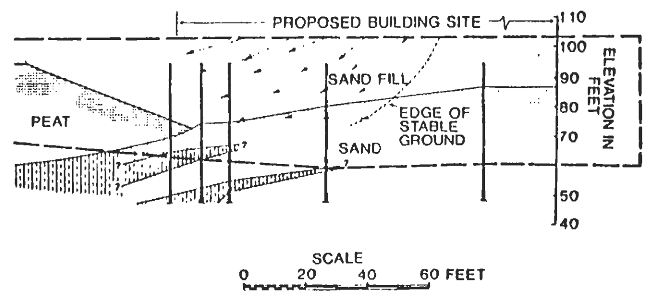

FIGURE 10 Vector displacement pattern in sand fill.

The displacement pattern predicted within the sand fill is also shown in Figure 10. During actual construction, the fill was instrumented with settlement plates and inclinometer casings to check the analytical results. Although the actual construction sequence and configuration of the sand fill were somewhat different than originally planned and assumed for analysis, many aspects of the study were still applicable for comparison of field behavior with the analytical results. In general, the predicted relationships of vertical settlements to horizontal spreading and the limits of stable zones within the sand fill were found to be in good agreement with actual behavior.

On the basis of analyses of several different profiles, it was generally concluded that the location and shape of the edge boundary of the stable zone within the sand fill model depended on

- The shape of the settlement profile resulting from compression of the organic layer;
- The magnitude of the settlements;
- The depth to the compressive layer underlying the fill; and
- The fact that as the depth of the compression layer increases, the average inclination of the boundary of the stable zones appears to become steeper.

SUMMARY AND CONCLUSIONS

The development of peat deposits poses significant problems for the geotechnical engineer as well as the developer. The physical and engineering characteristics of the organic materials are quite dissimilar from those of typical mineral-type soils for which theoretical relationships and modeling techniques have been developed to predict performance. As a result, much of the ability to predict the performance of peat under short- and long-term loading comes from direct observation and empirically derived relationships.

In developing peat deposits, the first choice is usually to completely remove and replace the peat materials with compacted sand fill. Such excavations must be well planned and controlled. However, excavation and replacement are not always economically practical, and there are additional problems with disposal of the excavated materials.

A variety of lessons was learned during development of peat deposits at Walt Disney World in Florida. The types of construction equipment and procedures used to excavate or partially excavate such materials depended on the total depth of the organics, the size of the area to be excavated, and the seasonal groundwater conditions. Surcharging techniques were used to complete primary consolidation before construction and to reduce the rate of secondary compression. This approach is not unique and has been used successfully by others (2-5). For this project, it was found that gross settlement and time rate predictions, made using Equations 1 and 2 after MacFarlane (2), provided good estimates for planning purposes. However, the primary judgment about when to remove the surcharge was based on monitoring actual field settlements during the surcharge program.

To a large extent, working with peat is a "learn by doing" proposition. When concerned with developing peat sites, both the geotechnical engineer and the developer should recognize the need to maintain flexibility in design schedules to cover the uncertainties in the predictions. As experience on a site is gained, the ability to predict peat behavior improves. Peat materials do lend themselves to engineering logic, but the logic uses direct practical experience to empirically adjust the predictions made from laboratory tests and analytical theories.

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