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Embankments Built Over Swamps

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SYNOPSIS Time and environmental constraints necessitated the development of unique methods for building earthen embankments over very deep and soft swamp deposits. Three case histories are presented. Construction techniques included alternate strip embankments, use of flexible vertical and horizontal drains, use of wood chips and high strength geotextile and the conventional stage and preloading techniques. In all cases, field instrumentation including pore-pressure/settlement transducers was installed to monitor the fill placement. The monitoring results were fed into a computer to determine the safety factor against shear failure and amount of settlement. The field monitoring results and predicted values agreed very well.

INTRODUCTION

Development of lands over extremely soft soils or swamps becomes increasingly necessary due to the depletion of firm grounds. To compound the problem, building embankments over swamps often results in different forms of shear failures, heaving and excessive lateral soil movements which are prohibited due to environmental restrictions. Engineers are searching for various means to carry out the construction safely and economically.

During the last five years, we have consulted on many projects involving embankments constructed over swamps. Among those projects, we selected three cases for which we performed extensive consultation followed by comprehensive monitoring programs. Consequently, much experience was gained. Some unique features of each of the three projects are given below. Other common features are given subsequently.

I. Eden Prairie Project

A. Construction of alternate embankment strips to provide a working platform for heavy construction equipment.

B. The use of plastic drain tiles to accelerate lateral drainage through fill soils.

C. Considerable savings of construction time and money.

II. Snelling Lake Dike

A. Construction of a layer of geotextile reinforced wood chips to provide a working platform for heavy construction equipment.

B. Considerable savings of construction time and money.

III. Clearwater County Highway Embankment

A. The use of wood chips to construct the lower portion of the embankment.

B. The use of tension geofabric to assure a uniform settlement.

In addition to the unique features of each project, other features common to all three projects are given below.

A. The use of Alidrains to accommodate rapid and continous vertical drainage through peats.

B. Placement of soil fill in stages to avoid shear failure which was the most critical governing factor of these projects.

C. A very good agreement between monitoring results and predicted values for embankment settlement.

UNIQUE CHARACTERISTICS OF SWAMP DEPOSITS

Swamp deposits possess some special characteristics compared with mineral soils. More distinctive properties which were taken into consideration in project design for the three cases include the following:

1. Primary consolidation of large magnitudes occurs rapidly.
2. Secondary compression takes place during a long period of time.
3. The transitional zone between primary consolidation and secondary compression cannot be readily determined based on consolidation theory.
4. Permeability decreases asymptotically as consolidation increases.
5. Horizontal permeability is much greater than vertical permeability.
6. Initial shear strength is extremely low but increases rapidly as consolidation takes place.

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DESIGN CONCEPTS

Because of the low initial shear strength of the swamp deposits, the initial layer of the embankment had to be distributed evenly. On the one hand, the initial layer had to be able to support heavy construction equipment. On the other hand, the initial layer of embankment should be placed in a manner such that no shear failures would result. Spencer's method of analyzing the general shapes of potential shear planes was employed for analysis.

Both vertical and horizontal drains were used. The spacing of the vertical drains was determined using the modified theory. The spacing varied according to the requirements of each project. Thicknesses of each subsequent fill stage were determined primarily by considering the stability of the slope. However, the actual thickness was adjusted based on the analysis of monitoring results which included both the rate and magnitude of the embankment settlement.

By comparing the monitoring results with the predicted values, the predicted settlement for the next stage was adjusted.

Because the applications of the consolidation theory to the construction of embankments over peat had to be modified, it was determined that field instrumentation monitoring was required for all three projects.

CASE I-EDEN PRAIRIE PROJECT

Project

This project is part of a shopping center development. It included a parking lot and storage area to be paved on an earthen embankment built over a swamp area inside a wetland. The maximum height of the embankment is about 25'. The critical area is about 600' by 800'.

This paper describes only the construction of the embankment in the critical area.

The owner of the project required that the project be completed in not more than two years. For environmental reasons, the adjacent wetland had to be protected against any disturbances as a result of the embankment construction; no shear failures or mud wave propagation toward the wetland were permitted.

Site and Soil Conditions

The project site is part of a 70 acre area to be developed into a shopping center. The site slopes down from a hill to a wetland on which the embankment would be constructed. The area described in this paper has a maximum of over 40' of peat and muck. The hill contains clay till and sand alluvium which were used as borrow materials for the embankment construction. A typical profile is shown in Figure 1.

The swamp deposits are very soft and compressible. Some pertinent characteristics are tabulated in Table 1.

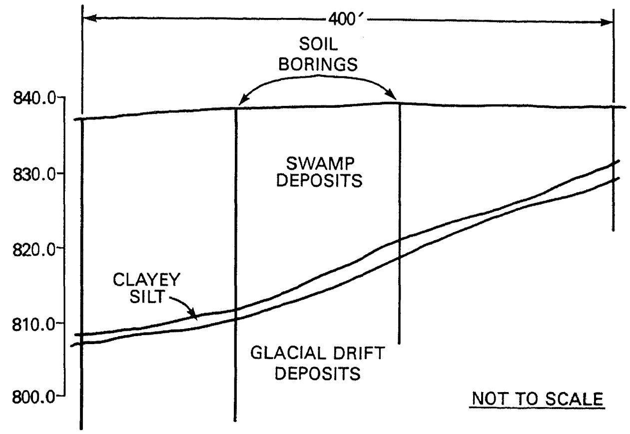

FIGURE 1 - TYPICAL SOIL PROFILE AT EDEN PRAIRIE PROJECT

TABLE 1
ENGINEERING PROPERTIES OF SWAMP DEPOSITS
EDEN PRAIRIE PROJECT

Property	Peat Fibrous	Muck Amorphous-Granular
Moisture Content (%)	350 to 650	100 to 200
Dry Density (pcf)	10 to 15	24 to 45
Liquid Limit (%)	350 to 550	100 to 200
Plastic Limit (%)	290 to 410	50 to 95
Specific Gravity (solids)	1.4 to 1.9	2.0 to 2.3
Vertical Permeability (cm/sec)	5.0×10^{-7}(1000) 4.4×10^{-8}(2000)	5.0×10^{-8}(1000) 1.7×10^{-8}(2870)
Horizontal Permeability to Vertical Permeability Ratio	2.7 to 3.0	3.0 to over 10.0
Undrained Shear Strength (psf)	70 to 200	100 to 160

Note = Numbers within brackets represent consolidation loads in psf.

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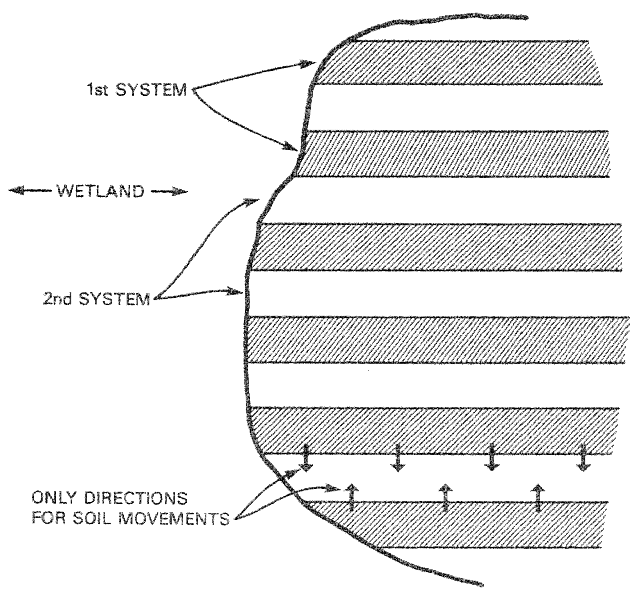
Construction Procedures

Working Platform

To begin the construction, a working platform was constructed. A layer of geotextile was sewed together and laid on the peat in the construction area. A system of 24' wide sand road embankments was constructed on 40' centers. Figure 2 shows the configuration and construction of these road embankments. The embankment strips were then observed for their settlement as well as stability against shear failures. Because of the strip embankment configuration, shear failures could only take place inside the gaps. That, in fact, provided a series of "trial embankments" for engineering observations.



(a) CONFIGURATION OF ALTERNATE EMBANKMENT STRIPS

(b) PLACEMENT OF SECOND SYSTEM STRIP EMBANKMENTS

FIGURE 2 - WORKING PLATFORM FOR EDEN PRAIRIE PROJECT

After the first system of the embankment strips settled and became stable, the gaps were covered with the second system of road embankments to complete the construction of the working platform. As a result of the stabilizing effects of the first system of road embankments, the working platform was stable against shear failures toward the adjacent wetland.

Installation of Alidrains

To provide vertical flow channels in the swamp deposits, vertical plastic drains (Alidrains) were installed. Selection of Alidrains was due to their extremely flexible structure.

A specially made stitcher consisting of a feed mandrel was mounted on a wide track backhoe for installation of the Alidrains. The hydraulic ram of the backhoe pushed the stitcher to the pre-determined depths in or below the swamp deposits. A strip of Alidrain followed the feed mandrel to the determined depth. When the mandrel was withdrawn, the Alidrain was anchored in position. The Alidrain was then cut about 1' above the ground surface. A photograph in Figure 3 shows the Alidrain installation.

FIGURE 3 - INSTALLATION OF ALIDRAINS AT EDEN PRAIRIE PROJECT

The spacing and depths of the Alidrains varied depending on the thicknesses of the swamp deposits and the underlying clay layer and the long term function of the embankment at different locations. Both 6' and 8' spacings were used in a triangular configuration for this project. The length of the Alidrains ranged from 30' to 50' as illustrated in Figure 4.

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Results

As described previously, the field instrumentation was monitored during each stage of fill placement. With the monitoring program being carried out as designed, the construction of the embankment was completed in one year. No shear failures toward the wetland were evidenced. As a comparison, if conventional methods were used to build the embankment, it would have taken about three to five years to complete this project. Consequently, it resulted in 80% cost savings.

The data obtained from the field instrumentation compared very well with the predicted values. Figure 5 shows the comparison. It can be seen in the figure that the maximum settlement was on the order of 13 1/2'.

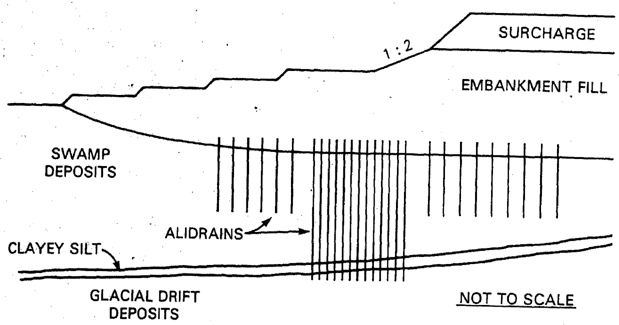

FIGURE 4 - TYPICAL ARRANGEMENT OF ALIDRAINS FOR EDEN PRAIRIE EMBANKMENT

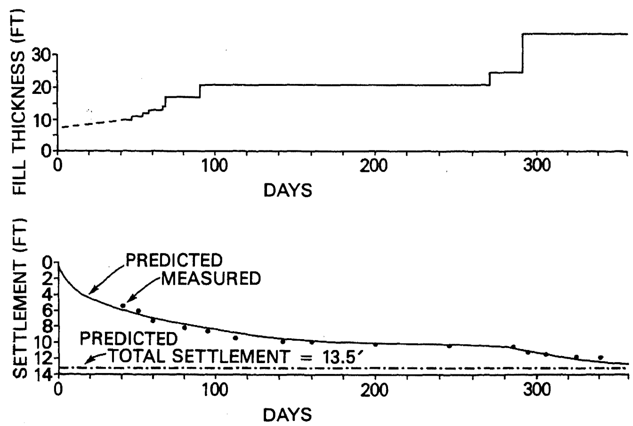

FIGURE 5 - SETTLEMENT OF EDEN PRAIRIE EMBANKMENT

Horizontal Drains

In order to provide access for water escaping from the Alidrains, plastic drain tiles were placed at 10' centers on the working platform. A large quantity of water flowing through these drain tiles was expected as a result of the rapid initial deformation of the peat. The water was directed to the adjacent wetland.

Field Instrumentation

The installation of pore-pressure and settlement gauges and settlement plates was carried out concurrently with laying of the horizontal drain tiles. The instrumentation consisted of three rows of devices which were aligned in the direction perpendicular to the toe line of the embankment. The devices were installed at mid height as well as on top of the swamp deposits.

The instrumentation was monitored frequently immediately after each fill stage was placed. Results of the monitoring were fed into the computer to check both the settlement prediction and slope stability. Based on the computation results, decisions were made regarding when the next fill stage should be placed. Time delay for fill placement was required when safety factor against shear failure was below 1.1. Also, the empirical equation for predicting the embankment settlement was modified.

Placement of Soil Fill

Each stage of the soil fill was placed after the computations indicated a potentially stable condition under the new fill. The soil fill consisted predominately of granular soils excavated from the adjacent high ground.

Fill materials were placed in stages varying in thickness from 3' to 6' to surcharge level. The height of surcharge varied from 10' to 15'. The side slopes of the embankment were maintained in a one vertical on two horizontal ratio.

CASE II - SNELLING LAKE DIKE

Project

For flood control purposes, a retention basin was constructed at the southern part of Snelling Lake. This paper presents only the construction of the dike built across the lake as a barrier for the flood water. The dike is about 500' long with a maximum height of 15'.

Construction scheduling required the embankment dike to be completed in about one year. Because the dike was adjacent to a recreational area, the owner posted a no shear failure restriction during or after the construction period. Because the dike serves as a link between the entrance of the park and a hiking trail, and for other aesthetic reasons, soil fill had to be used to construct the dike. The slopes of the dike had a slope ratio of 1 vertical on 3 horizontal.

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Site and Soil Conditions

The project site is located over a swamp adjacent to the lake. Some water was ponding in the area during the site investigation.

The soil profile consists predominately of peat, (maximum thickness of about 55') underlain by a siltstone bedrock. A typical soil profile is shown in Figure 6.

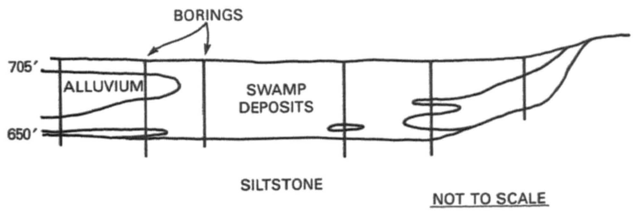

FIGURE 6 - TYPICAL SOIL PROFILE AT SNELLING LAKE SITE

The consistency of the peat is extremely soft. Some pertinent properties of the peat are tabulated in Table 2.

TABLE 2
ENGINEERING PROPERTIES OF PEAT
SNELLING LAKE DIKE

	Peat Fine Fibrous
Moisture Content (%)	200 to 350
Dry Density (pcf)	10 to 20
Liquid Limit (%)	180 to 300
Plastic Limit (%)	100 to 200
Specific Gravity	2.07
Vertical Permeability (cm/sec)	1.0×10^{-5}(200) 7.0×10^{-6}(500) 1.0×10^{-6}(1000) 1.0×10^{-7}(2000) 1.0×10^{-8}(4000)
Horizontal Permeability to Vertical Permeability Ratio	1.5 to 2.0
Undrained Shear Strength (psf)	90 to 150

Note: Numbers within brackets represent vertical consolidation loads in psf.

Construction Procedures

Working Platform

A layer of geotextile about 200' x 500' in size was laid on the surface of the swamp. A small dozer spread about 3' of wood chips on the geotextile. Another layer of geotextile was laid on the wood chips before a total of 6' of wood chips were placed. For equipment travel, 1' of gravel was placed on top of the wood chips. Figure 7 shows a small dozer constructing the second layer of the wood chips.

FIGURE 7 - CONSTRUCTION OF WORKING PLATFORM WITH WOOD CHIPS

Installation of Alidrains

Similar to the Eden Prairie project, the vertical flow channels in the peat were provided by Alidrains. The installation procedure of the Alidrains is similar to that described previously. The maximum length and spacing of the Alidrains were about 60' and 10', respectively. Because of the length, a crane with a 100' boom was utilized to install the Alidrains as shown in Figure 8. All of the drains were anchored near the siltstone beneath the peat.

Field Instrumentation

After the installation of the Alidrains, pneumatic gauges were installed at various depths in the peat. During construction, the gauges were monitored daily. Results of the monitoring data were fed into a computer for computations of embankment stability and amount of settlement. In addition, the settlement predictions were compared with the actual values and revised for subsequent stage fill placements.

Time delay for placement was imposed when a safety factor lower than 1.1 was indicated by the computation.

Placement of Soil Fill

Silty sand was used to build the dike. As a design requirement, each stage of the fill was not to exceed 3'. Similar to the Eden Prairie project, each stage was placed after a required safety factor was obtained. Thicknesses of the fill were changed accordingly dependent on time and safety. About 3' of surcharge was placed on the dike.

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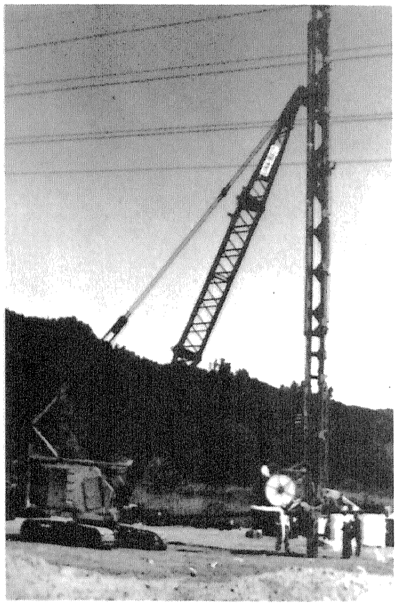

FIGURE 8 - INSTALLATION OF ALIDRAINS AT SNELLING LAKE DIKE

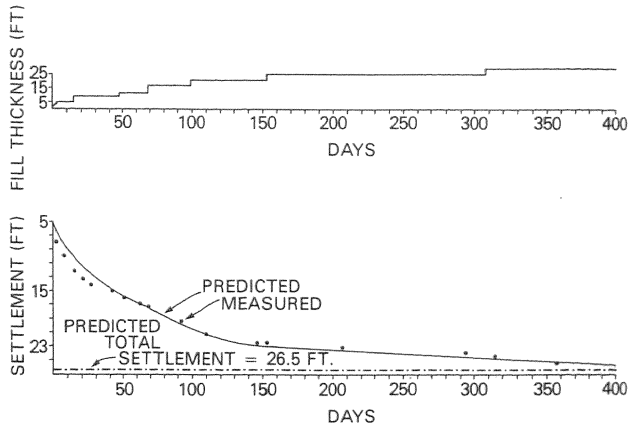

FIGURE 9 - SETTLEMENT OF SNELLING LAKE DIKE

Because of time constraints, the surcharge fill was removed earlier than planned. Therefore, reduction of the secondary compression of the peats was not maximized.

Results

The monitoring program greatly assured the success of this project. The dike was built without any shear failure and disturbance toward the adjacent swamp area in the lake. The dike was built in 10 months. The cost saving amounted to over two-thirds of the conventional method.

As a result of the peat consolidation, the final height of the dike is about 41' of which the lower 26 1/2' submerged or sank below the original surface of the swamp.

Both the monitoring data and predicted values of the settlement are shown in Figure 9. The figure shows a very good agreement of the two during the entire duration of the construction.

CASE III - CLEARWATER COUNTY HIGHWAY

Project

A state aid highway in northern Minnesota was upgraded requiring the placement of a 15' high embankment over very soft swamp deposits. The wetlands are a very environmentally sensitive area adjacent to the Mississippi River near Itasca State Park.

The main engineering problem on this project was the existence of twin 16" high pressure petroleum pipelines buried within the peat deposits adjacent to the highway. The road embankment fill had to be placed on the 20' to 30' deep peat deposits without displacing the pipelines laterally more than 3". Excessive strains on the welded steel pipeline would have caused possible failure of the welds and catastrophic leakage of the petroleum.

Site and Soil Conditions

The project site is located adjacent to the Mississippi River north of Itasca State Park in Clearwater County, Minnesota. The subsurface profile consisted of 20' to 30' deep peat and muck deposits overlying glacial drift deposits. Figure 10 shows a cross-section of the embankment and soil profile.

The peat and muck were extremely soft and similar to that encountered in the previous two projects. Some pertinent properties of the peat are tabulated in Table 3.

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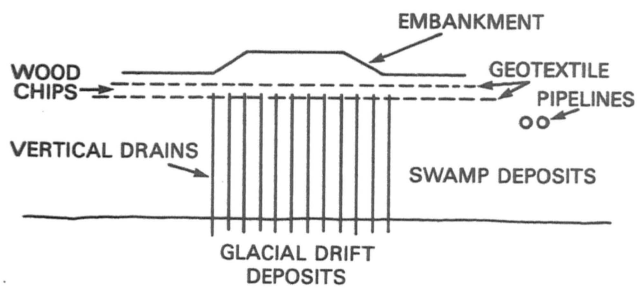

FIGURE 10 - CROSS–SECTION OF HIGHWAY EMBANKMENT

TABLE 3

ENGINEERING PROPERTIES OF PEAT
CLEARWATER COUNTY HIGHWAY

Property	Peat Fibrous	Muck Amorphous-Granular
Moisture Content (%)	250-600	150-250
Dry Density (PCF)	12-16	25-30
Liquid Limit (%)	300-450	150-250
Undrained Shear Strength (PSF)	90-180	130-250

Construction Procedures

Wood Chip Platform

A 5' thick platform of wood chips was used to minimize the weight of the embankment, thereby increasing the factor of safety. The existing road fill and underlying corduroy material was excavated and replaced with compacted wood chips. Figures 11 and 12 show the construction of excavating the existing road fill and replacing it with wood chips.

Alidrain Installation

Vertical plastic drains (Alidrains) were installed in order to accelerate the consolidation and thereby the shear strength of the swamp deposits. The drains were put down on an 8' square grid pattern in the majority of the swamp deposits. In the area adjacent to the pipeline, the drains were put down on a 4' square grid.

It was found on this project that the surface of the wood chips was very stable and adequately supported the backhoe-mounted Alidrain installation equipment. A total thickness of 5' of wood chips was used to support the equipment. After the vertical drains were installed, the thickness of the wood chip layer was cut down to about 3' thick because total settlements were estimated to be less than 5' in some areas.

As the fill was pushed off to the sides with a dozer, the vertical drains neatly sheared off at the surface.

FIGURE 11 - EXCAVATION OF EXISTING ROAD FILL

FIGURE 12 - REPLACEMENT WITH WOOD CHIPS

Reinforcement Fabric

In order to increase the factor of safety and thereby minimize lateral movements of the pipeline, a very high strength geotextile woven fabric was placed above the wood chip layer and covered with the embankment fill. The fabric chosen was Geolon 1250 which has a very high tensile strength and modulus. The geotextile was covered with embankment fill by filling from the outer edges toward the middle. This was to anchor the edges so that maximum stresses could be developed in the fabric.

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Field Instrumentation

Field instrumentation similar to that described in the previous two projects was used to monitor settlements and consolidation rates. The placement of the individual stages of fill was controlled using the field data.

A total of six inclinometers were also installed to monitor lateral movements of the swamp deposits. The lateral movement of the pipeline was the critical concern on this project. A total of three inclinometers were placed at a test station approximately 300' away from where the pipeline was adjacent to the embankment. In addition, three inclinometers were placed at the critical pipeline section. The inclinometer station at Station 34+00 was used as a test station where filling was done and lateral movements were analyzed before any further fill was placed near the critical pipeline.

Figure 13 is a photograph of the three inclinometers at the test station at Station 34+00. The three inclinometers were 10', 20' and 30' away from the toe of the stabilizing berm of the embankment. Also shown on Figure 13 is the read-out terminal for the pneumatic instrumentation.

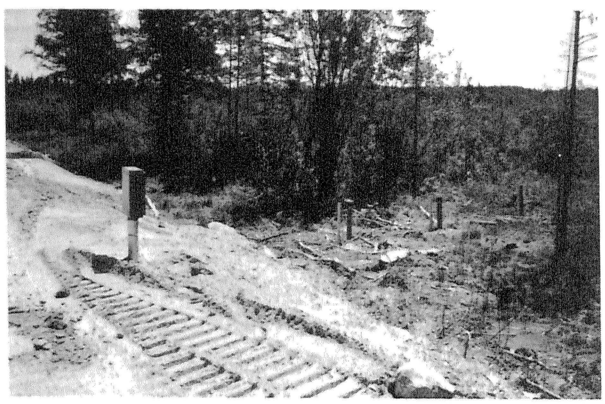

FIGURE 13 - INSTRUMENTATION AT STATION 34+00

Stage Fill Placement

The fill was placed in three 5' stages. There was approximately one to two months time delay between placement of the three stages.

Placement of the fill was controlled very closely in the field. The instrumentation was monitored and placement was controlled to keep the lateral displacement of the pipeline to within acceptable amounts.

Results

The entire height of fill plus surcharge was successfully completed in the fall of 1983. The surcharge will remain in place until the spring of 1984 and then the surcharge will be removed and the road paved.

At the time of preparation of this paper, Stage II was in place. Lateral movements at the test station at Station 34+00 indicated deflections on the order of 5" at the inclinometer nearest the toe of the embankment. Lateral deflections at Station 31+50, where the pipeline is located, indicated movements on the order of 1". Figure 14 shows a plot of the readings for the two referenced inclinometers.

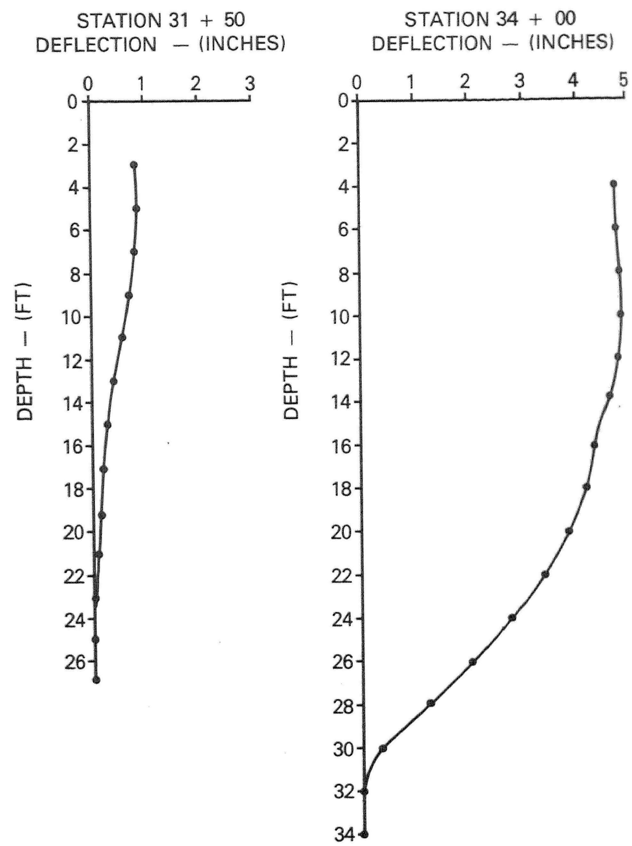

FIGURE 14 - INCLINOMETER READINGS AFTER STAGE II FILL PLACEMENT

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DISCUSSION AND COMMENTS

The three successful cases presented in this paper were constructed in different years between 1979 and 1983. Vast experience was obtained after the completion of each of these projects. As a result, methods for embankment construction over swamps are constantly revised and improved to optimize the design. The authors feel that the revisions of the design methods are necessary because direct applications of the soil mechanics theory may lead to an unsatisfactory or even an unsafe design.

The experiences gained through construction of these projects assisted the authors in consultation on other similar projects. Good results were realized in other projects which are not described in this paper. However, details of the design methods are being written for other technical publications.

Based on experiences gained by the authors, several factors should be regarded as major contributors to the success of these projects. The factors are summarized below.

1. Because a large amount of consolidation is usually experienced in swamp deposits, extremely flexible plastic drains should be used to provide the vertical flow channels for pore water in the peat. Equally important as flexibility is the continual functioning of the drains vital to the embankment construction. This assures the flowage of the pore water escaping as a result of the consolidation. In the author's opinion, Alidrains meet these requirements extremely well.

2. To support construction equipment on swamp deposits, the construction of a working platform is essential. The alternate strip method provides an excellent means if soil fill has to be used. However, when wood chips are available, they are an excellent lightweight fill material.

3. The use of geotextile increases the overall resistance against rotational and punching shear failures, and lateral displacement.

4. In general, soil mechanics consolidation theory can be employed to predict settlement of the swamp deposits. However, because the transitional zone between the primary consolidation and secondary compression cannot be clearly defined, modification of the theory should be made.

5. Due to the unique characteristics of the swamp deposits, some laboratory test modifications should be made to obtain the design parameters. Modifications should be made for the following tests:

   A. Each increment of the consolidation test should be made on a new individual sample.

   B. Coefficients of permeability in the horizontal direction should be determined for designing the Alidrain spacing and length. Because of the large volume change under consolidation load, long samples should be prepared for load history simulation before the permeability tests.

6. A well designed field instrumentation monitoring program should be performed for embankment construction over swamps whenever time and construction costs are vital for the project.

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Eden Prairie Project -

Civil Engineers:Suburban Engineering, Inc.
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Alidrain Installation:Vibroflotation Foundation Co.
Pittsburgh, Pennsylvania
Contractor:Rietmann Contracting, Inc.
Contractor:Leon Joyce Construction Company

Snelling Lake Dike -

Owner:Metropolitan Airport Commission, Minnesota
Civil Engineers:Eugene A. Hickok and Associates, Inc.
Wayzata, Minnesota
Alidrain Installation:Vibroflotation Foundation Co.
Pittsburgh, Pennsylvania
Contractor:G & L Contracting
Subcontractor:Ames

Clearwater County Highway Embankment -

Owner:Clearwater County Highway Department
Bagley, Minnesota
Civil Engineers:Toltz, King, Duvall, Anderson & Assoc.
St. Paul, Minnesota
Alidrain Installation:Vibroflotation Foundation Co.
Pittsburgh, Pennsylvania
Contractor:Rajala Construction Company
Cohasset, Minnesota

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