Settlement Rates in the Varved Clays of the Hackensack Meadowlands

A. A. SEYMOUR-JONES

ABSTRACT

Field settlement and piezometer data for four highway construction projects have been used to determine the effective rates of consolidation in the varved clays of the Hackensack meadowlands. The data were used to evaluate the relative performance of sand drains installed by displacement and nondisplacement methods and areas where sand drains were not used. The effects of the use of sand drains and sand drain spacing are evaluated.

Field settlement and piezometer data have been analyzed for four highway construction areas in the Hackensack meadowlands to determine the effective field rate of consolidation. These data are compared with laboratory and field permeability tests that were made as part of the original design. The field consolidation data were also used to evaluate the effectiveness of sand drains, the relative efficiency of displacement and nondisplacement sand drains, and the effect of sand drain spacing on the rate of consolidation.

LOCATION

The Hackensack meadowlands are located in northeastern New Jersey, approximately 3 miles west of New York City as shown in Figure 1. This site is a former glacial lake that extended over a considerably larger area known as Glacial Lake Hackensack (1). The four highway construction areas analyzed are portions of the New Jersey Turnpike and are labeled A, B, C, and D in Figure 2.

GEOTECHNICAL CHARACTERISTICS

Typical boring logs for these four areas are shown in Figures 3-6. The general soil profile consists of a surface layer of peat, which has been covered or replaced by fill in built-up areas, underlain by a sand layer in most locations. The varved clays that are the topic of this paper are located beneath this sand layer. The varved clays range from 65 to 130 ft in thickness at these locations. Beneath the varved clays is a sand and gravel glacial till layer that overlies a shale and sandstone bedrock.

The varved clays consist of individual varves 1/16 to 1/2 in. thick. Each varve consists of a spring-summer deposition that varies from a fine sand or silt to a clayey silt and a fall-winter deposition that varies from a silty clay to a clay. Close visual analysis of many boring samples shows that the initial spring deposition is a very thin parting of fine sand or silt overlain by the clayey silt deposited during the remainder of the spring-summer period. In some samples this sand or silt parting was missing. Figure 7 shows plasticity data
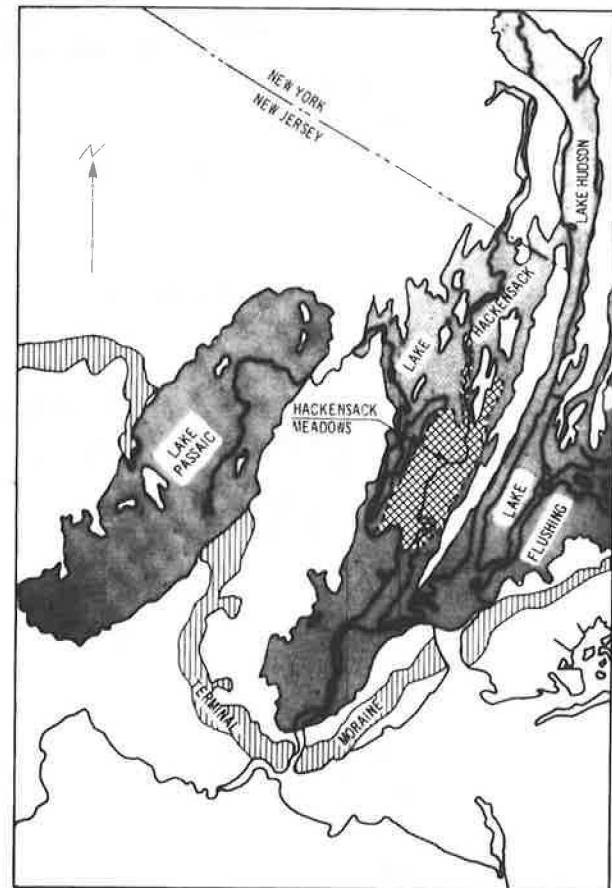

FIGURE 1 Glacial geologic setting of the Hackensack meadowlands.

for whole varves and for the separate varve components.

The boring profiles in Figures 3-6 are for the four areas and show that the upper 20 to 30 ft of the varved clay have been desiccated resulting in overconsolidation of the deposit beneath this desiccated crust by 0.5 to 2.0 tsf. These four figures show that conditions within the varved clay are very similar at areas A, C, and D where the overconsolidation due to desiccation is approximately 0.5 tsf. The overconsolidation at area B is significantly greater, approximately 2.0 tsf, as shown in Figure 4. The effect of this greater overconsolidation on the shear strength can also be seen in this figure. The present overburden pressure or overburden pressure noted in these four figures is the overburden pressure before construction of the highway projects discussed in this paper. Imposed highway embankment loads for these areas ranged from 0.6 to 1.8 tsf.

Numerous horizontal permeability tests, both laboratory and field, were made on these varved clays as part of the original highway design. Figure 8 shows permeability test results for area C, which
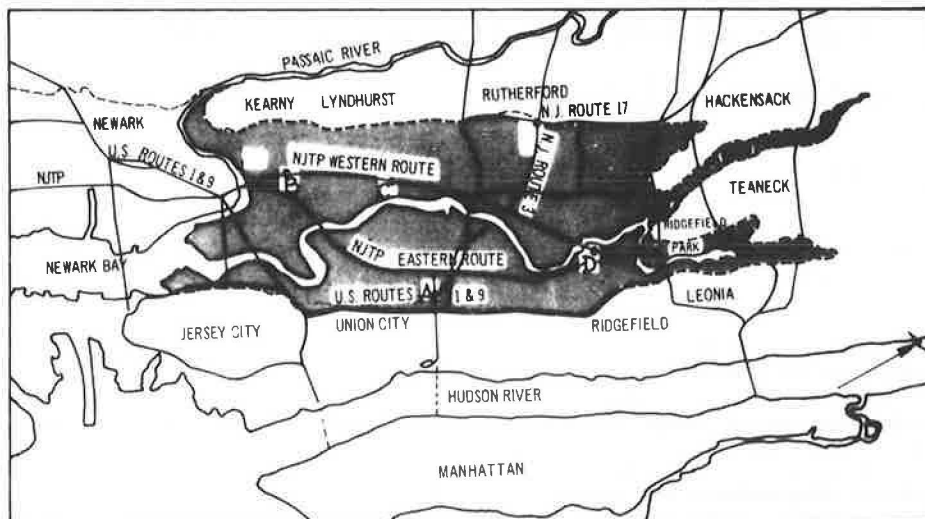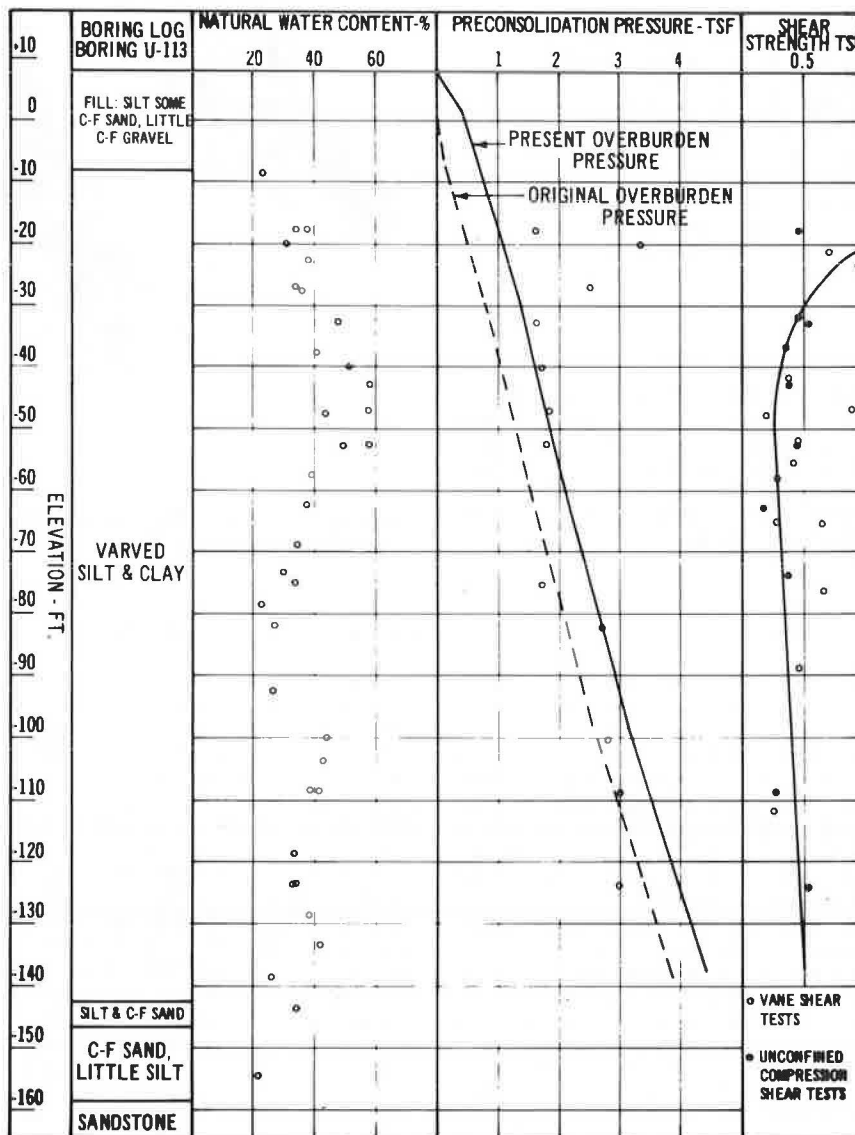
FIGURE 2 Location of study areas.

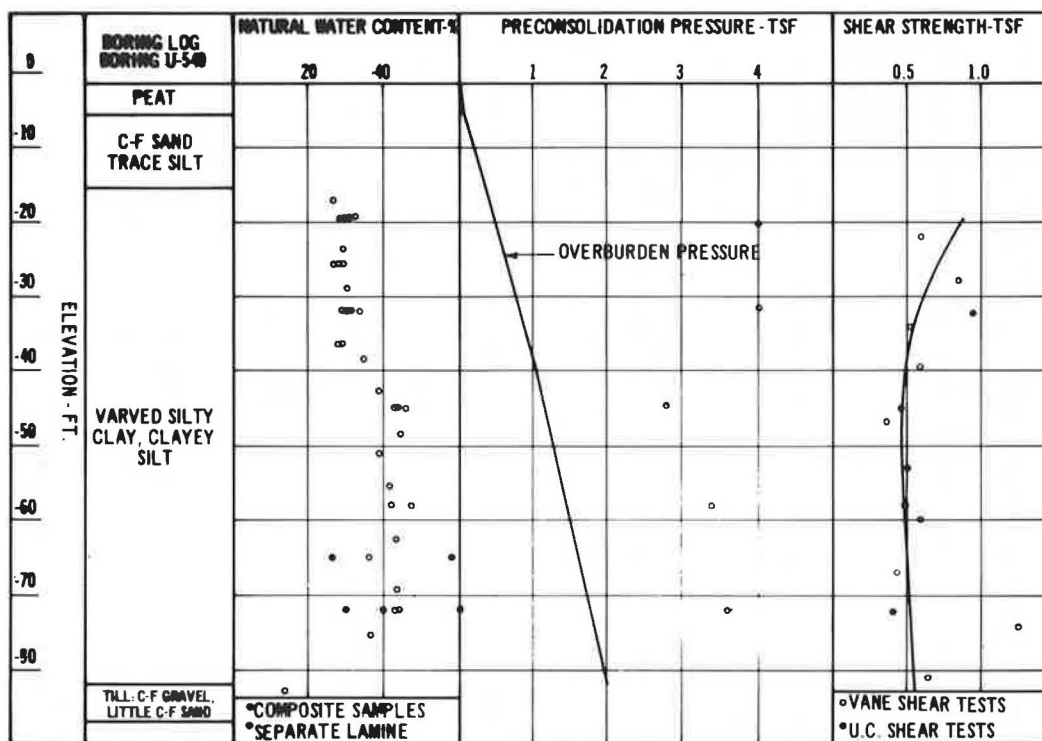FIGURE 3 Typical boring log for area A.

FIGURE 4   Typical boring log for area B.

Figure 4 chart labels:

BORING LOG BORING U-548	NATURAL WATER CONTENT-%	PRECONSOLIDATION PRESSURE - TSF	SHEAR STRENGTH-TSF

ELEVATION - FT.

PEAT

C-F SAND TRACE SILT

VARVED SILTY CLAY, CLAYEY SILT

TILL: C-F GRAVEL, LITTLE C-F SAND

Water content axis: 20   40

Preconsolidation axis: 1   2   3   4

Shear strength axis: 0.5   1.0

OVERBURDEN PRESSURE

° COMPOSITE SAMPLES
• SEPARATE LAMINE

○ VANE SHEAR TESTS
• U.C. SHEAR TESTS

FIGURE 5   Typical boring log for area C.

Figure 5 chart labels:

BORING LOG BORING S-5.4	NATURAL WATER CONTENT-%	PRECONSOLIDATION PRESSURE TSF	SHEAR STRENGTH TSF

Water content axis: 20   40   60

Preconsolidation axis: 1   2   3

Shear strength axis: 0.5   1.0

ELEVATION - FT.

MISCELLANEOUS FILL

ORGANIC SILT

SILT, SOME F SAND

VARVED SILTY CLAY

VARVED SILTY CLAY WITH SAND AND SILT LENSES

SHALE

P.L.   L.L.

PRESENT OVERBURDEN PRESSURE

ORIGINAL OVERBURDEN PRESSURE

○ COMPOSITE SAMPLES
• SEPERATE LAMINIE
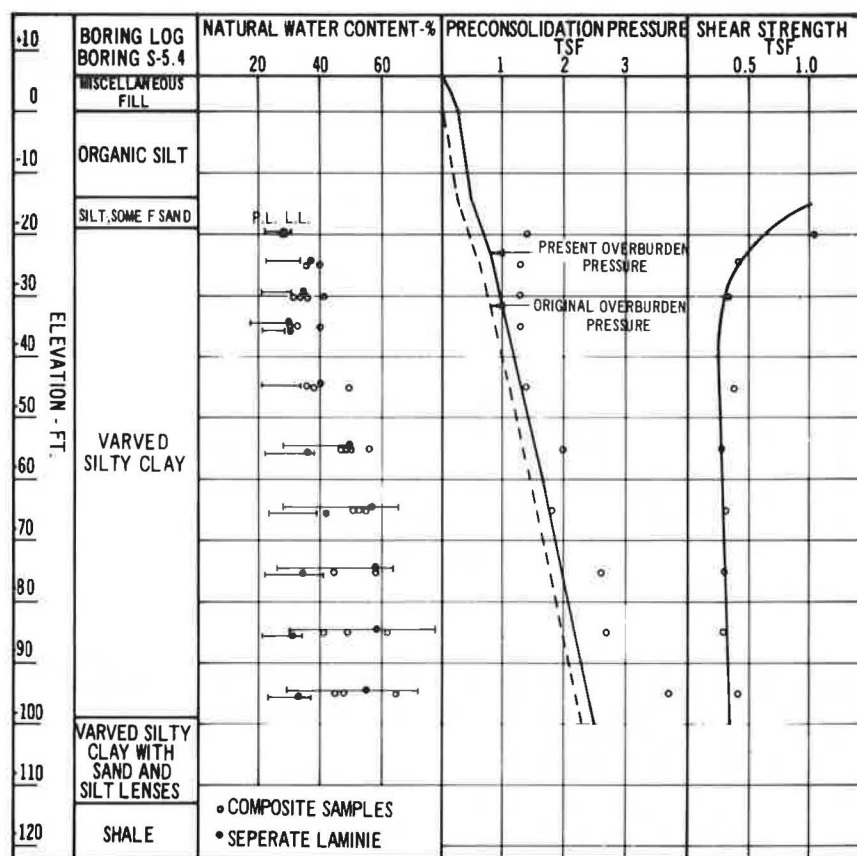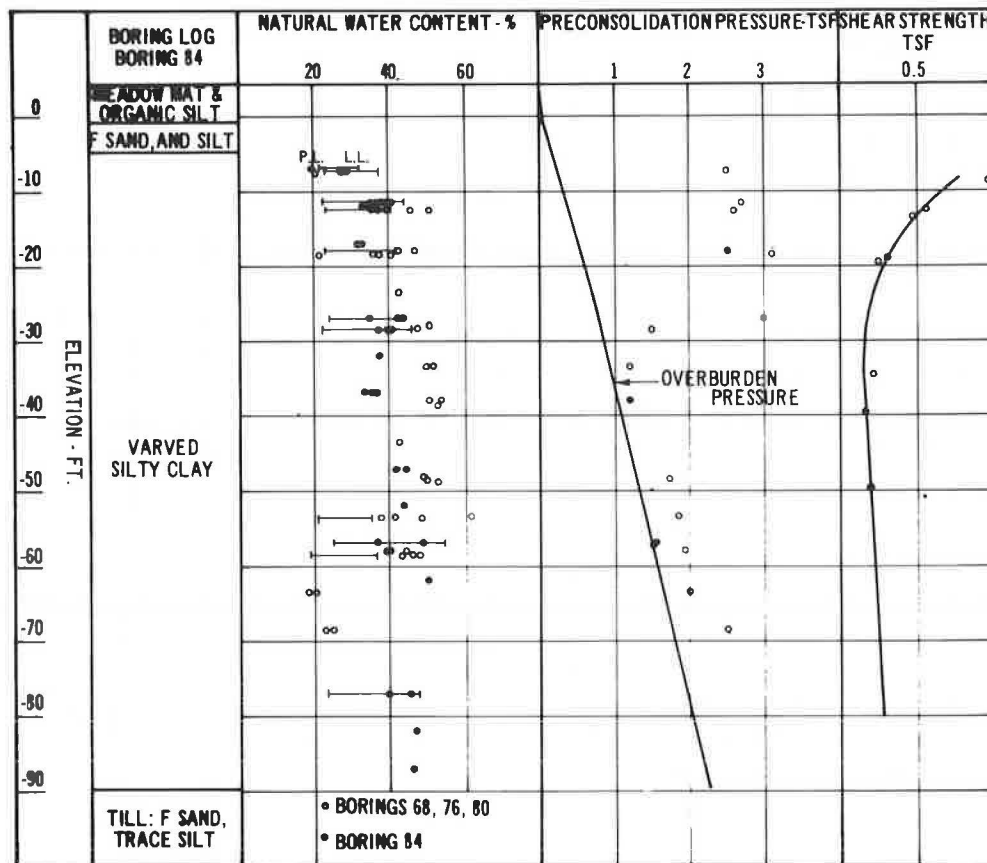
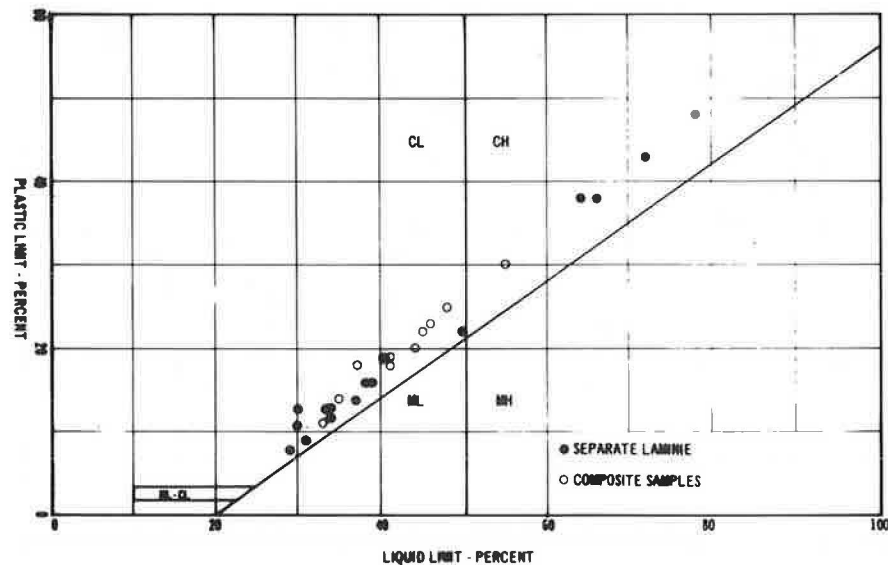FIGURE 6   Typical boring log for area D.

FIGURE 7   Atterberg limit data for varved clays.

are typical for these varved clays. Included in this figure are two large-scale permeability tests made on individual sand drains by Casagrande and Poulos (2). These tests consisted of a single wash sand drain and a single driven sand drain that were instrumented with adjacent piezometers to determine the effective rate of horizontal permeability for each. Casagrande and Poulos (2) have shown the horizontal permeability to be 8 to 20 times greater than the vertical permeability for these varved clays.

Permeability data obtained from areas B and D are similar to those for area C. The noticeable decrease in permeability with depth is significant.

EMBANKMENT CONSTRUCTION METHODS

Typical sections of the embankment construction for non-sand drain and sand drain areas are shown in Figure 9. In the areas where sand drains were not
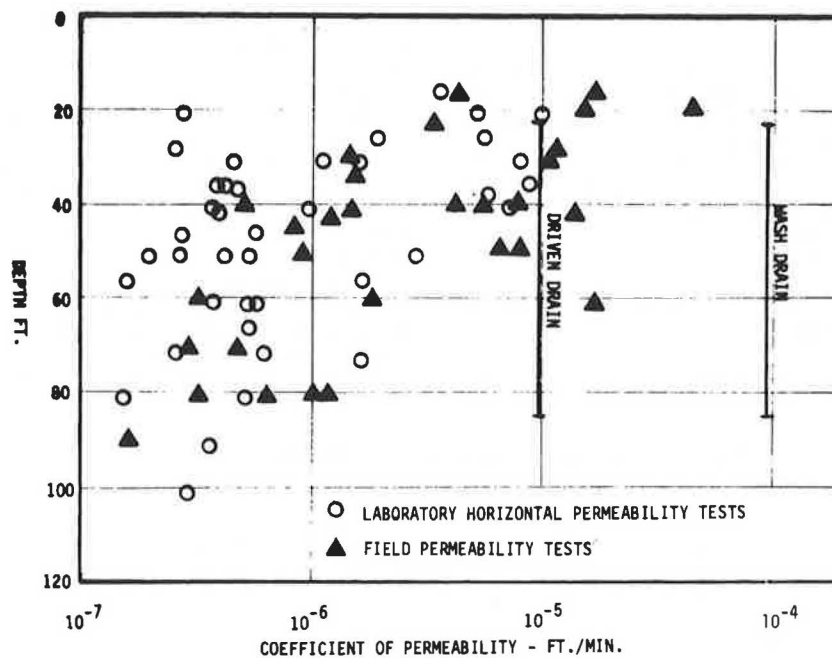
FIGURE 8   Laboratory and field permeability data for area C.

used the sequence of construction employed was to (a) excavate the surface layer of peat and then place clean backfill; (b) install settlement platforms, piezometers, and any other instrumentation; and (c) place the embankment fill at a controlled rate to maintain embankment stability. In the areas

where sand drains were employed the construction sequence was similar except that the sand drains were placed after the backfilling of the peat excavation and before the installation of the instrumentation.

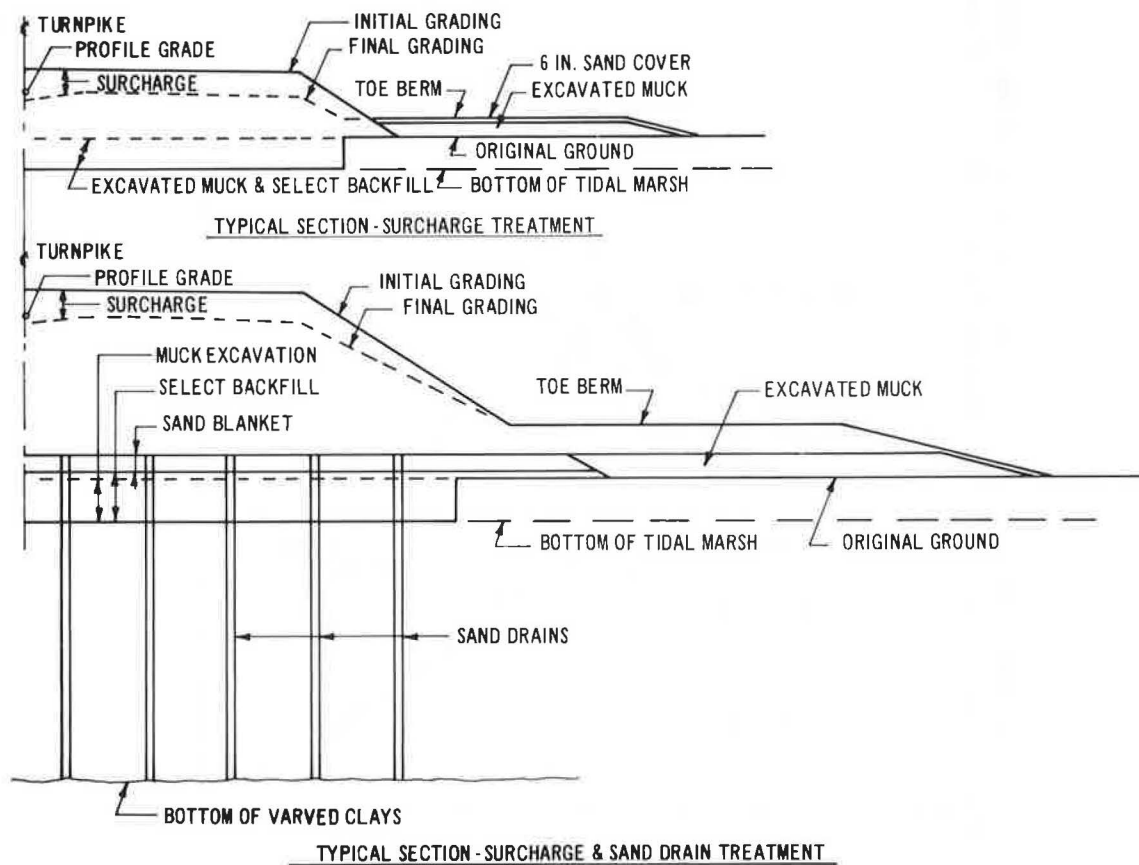Two types of sand drains were used: displacement

FIGURE 9   Typical embankment sections for area C.

and nondisplacement. The displacement sand drains were used in areas A, B, and D and were constructed by driving a closed-end, 18-in.-diameter mandrel and placing sand as the mandrel was withdrawn. The non-displacement sand drains used in area C were placed by the Raymond method, which consists of jetting a 20-in.-diameter hole with a fish-tail bit and jet pipe, inserting an 18-in.-diameter closed-end man-drel, and placing sand as the mandrel is withdrawn. Summaries of the treatment methods for the four areas are given in Table 1.

FIELD DATA AND ANALYSIS

The field data analyzed consisted of settlement readings obtained from settlement platforms and pore pressure readings obtained from piezometers located beneath the center of the embankments and within the varved clays below the upper desiccated portion at depths ranging from 30 to 100 ft below the original ground surface. Typical piezometer and settlement platform data for area C are shown in Figure 10. The platform settlement readings were plotted against the square root of time to determine the point of 90 percent theoretical consolidation as developed by Taylor (3).

The piezometer readings were analyzed using Skempton's relationship between applied pressure and pore pressure (4). Normally the values for Skempton's coefficient, A, are obtained from triaxial tests with pore pressure measurements. Because such

TABLE 1 Summary of Treatment and Observation Methods

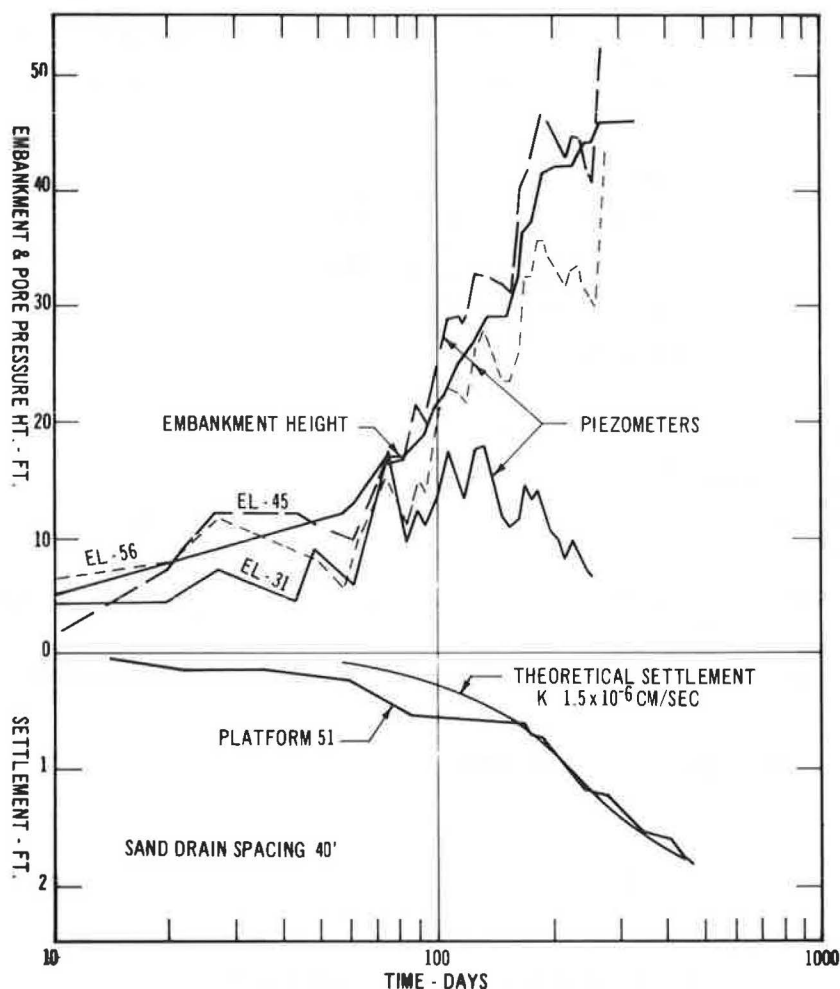| Area | Surcharge without Sand Drains | Treatment Methods and Sand Drain Spacing | | Observations | |
		Displacement Sand Drains (ft)	Nondisplacement Sand Drains (ft)	Piezometers	Settlement Platform
A		8, 10, 14			X
B		14		X	X
	X			X	X
C			20, 40	X	X
	X				X
D		14, 16, 20		X	X

FIGURE 10 Typical piezometer and settlement platform data for area C.

data were unavailable, values for A recommended by Skempton (4) were used: A = 1.0 for conditions where the applied load exceeded the soil preconsolidation pressure and A = 0.5 for conditions where the applied load was judged to be less than the soil preconsolidation pressure.

The previously noted field data provided the basis for calculating the coefficient of consolidation. The theory developed by Barron (5) was used for the areas where sand drains were employed. The methods of analysis developed by Fungaroli (6) and that developed by Davis and Poulos (7), which are based on horizontal drainage only, were used for the non-sand drain areas. A significant difference in the calculated coefficient of consolidation was obtained by the latter two methods and is discussed in the next section of this paper.

It was found that the range in values of the calculated coefficients of consolidation was four orders of magnitude. This range was much wider than expected. In an attempt to explain this wide range of results it was decided to use the calculated coefficient of consolidation data to calculate horizontal permeabilities that could be compared with results of laboratory and field horizontal permeability tests made during the design phases. The relationship between horizontal permeability and coefficient of consolidation is

$$K_h = C_r (\Delta\epsilon/\Delta P)\gamma$$

where

   K_h = horizontal permeability (cm/sec),
   $\Delta\epsilon$ = change in strain due to embankment load,
   ΔP = change in stress due to embankment load (kg/cm^2),
   γ = unit weight of water = 0.001 kg/cm^3, and
   C_r = coefficient of consolidation (cm^2/sec).

For the determination of $\Delta\epsilon$ and ΔP, calculated settlements were determined by use of one-dimensional consolidation tests. The value of $\Delta\epsilon$ determined was the total calculated settlement di-

vided by the varved clay deposit thickness. The ΔP used was the average imposed stress over the depth of this deposit. The calculated horizontal permeabilities are shown in Figure 11 and are summarized in Table 2. The equation is the classic consolidation equation developed by Terzaghi for consolidation by vertical drainage modified for horizontal drainage by Barron (5).

An independent assessment of the potential horizontal permeability of the sand and silt partings was developed using data provided by Burmister (8) and is discussed in the next section.

DISCUSSION

A comparison of the various permeability values calculated from the field settlement and piezometer data is worthwhile to evaluate the range of results and the probable causes of these variations. A comparison of these data with the laboratory and field permeability test results provides a basis for judging how useful the latter are for design.

Figure 11 shows the permeability values calculated using the field settlement platform and piezometer readings. The range of values is quite large, about four orders of magnitude. However, there are certain trends that can be observed from this plot. These trends are (a) the non-sand drain areas have much higher permeability values than the sand drain areas, (b) within each of the four separate construction areas the data for the sand drains cover a relatively small spread, and (c) the sand drain data for areas A and B are significantly smaller than those for areas C and D. The remainder of this discussion evaluates potential causes of these observed conditions.

Settlement Platform Versus Piezometer Data

The ranges of calculated horizontal permeability values based on piezometer data shown in Figure 11 are about two to three times the range of those calculated from settlement platforms in each of the
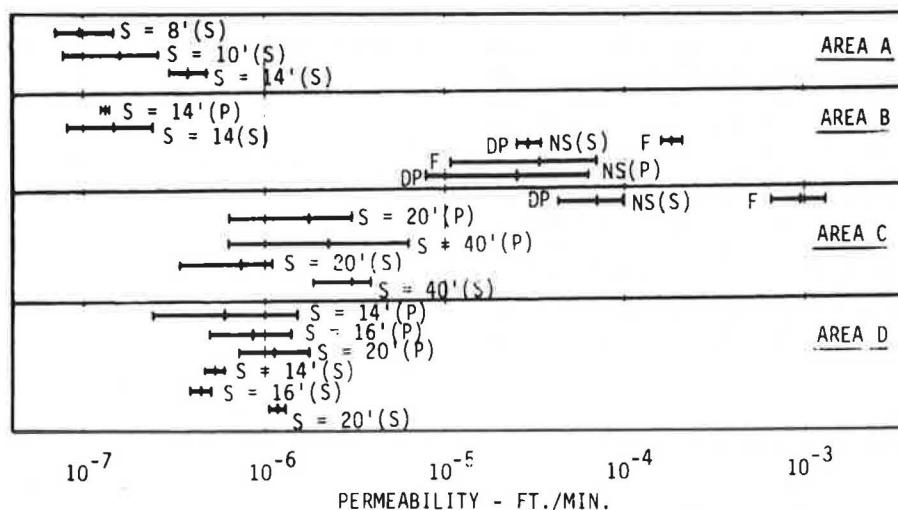
1 Method of analysis for non-sand drain areas; DP = Davis-Poulos, F = Fungaroli
2 Minimum permability value
3 Average permeability value
4 Maximum permeability value
5 Sand drain spacings; S = spacing, NS = no sand drains
6 Method of measurements; S = settlement platform, P = piezometer

FIGURE 11 Summary of calculated horizontal permeabilities from field settlement and piezometer data.

TABLE 2 Summary of Calculated Horizontal Permeabilities

Area	Sand Drain Spacing [ft (m)]	Data Source[a]	No. of Data	Horizontal Permeability [ft/min x 10^{-6} (cm/sec x 10^{-6})]		
				Maximum	Minimum	Average
A	8 (2.44)	S	6	.14 (.07)	.06 (.03)	.10 (.05)
	10 (3.05)	S	7	.26 (.13)	.08 (.04)	.16 (.08)
	14 (4.27)	S	6	.48 (.24)	.30 (.15)	.38 (.19)
B	14 (4.27)	S	2	—	—	.12 (.06)
		P	4	.24 (.12)	.08 (.04)	.14 (.07)
	n/s[b]	S	4	210 (105)[c] 36 (18)[d]	160 (80)[c] 26 (13)[d]	180 (90)[c] 30 (15)[d]
		P	2	72 (36)[c] 66 (33)[d]	10 (5)[c] 8 (4)[d]	34 (17)[c] 26 (13)[d]
C	n/s	S	9	1,260 (630)[c] 100 (50)[d]	640 (320)[c] 44 (22)[d]	1,120 (560)[c] 70 (35)[d]
	20 (6.10)	S	5	1.10 (.55)	.34 (.17)	.74 (.37)
		P	15	3.0 (1.5)	.60 (.30)	1.72 (.86)
	40 (12.19)	S	9	3.8 (1.9)	1.8 (.90)	3.0 (1.5)
		P	18	6.2 (3.1)	.60 (.30)	2.2 (1.1)
D	14 (4.27)	S	2	.56 (.28)	.46 (.23)	.52 (.26)
		P	7	1.52 (.76)	.24 (.12)	.60 (.30)
	16 (4.88)	S	2	.50 (.25)	.38 (.19)	.44 (.22)
		P	8	1.40 (.70)	.50 (.25)	.86 (.43)
	20 (6.10)	S	2	1.26 (.63)	1.04 (.52)	1.16 (.58)
		P	7	1.76 (.88)	.72 (.36)	1.12 (.56)

[a]S indicates data from settlement platform readings, P indicates data from piezometer readings.
[b]n/s indicates no sand drains used.
[c]Data based on Fungaroli method of analysis.
[d]Data based on Davis and Poulos method of analysis.

individual areas. This result is reasonable because the piezometers represent only conditions at a local point within the varved clay deposit, whereas the settlement platforms represent the average condition for the full depth of the deposit. Figure 8 shows, based on laboratory and field tests, a wide range of permeabilities due to the natural variability of the soil. This is confirmed by field piezometer data. It appears that averages of the permeability results from a number of piezometers in any area provide a reasonably good representation of the average horizontal permeability for the total varied clay deposit thickness as determined from the settlement platform data.

Comparison of Horizontal Permeability in Different Areas

Horizontal permeability data for areas A and B are about one order of magnitude smaller than those for areas C' and D. If only the data for sand drains with 14-ft spacing are reviewed (Table 3), the permeabilities for areas A and D are generally close together and significantly higher than those for area B. The one known significant difference between the soils of area B and those of the other two areas

TABLE 3 Selected Horizontal Permeability Data

Area	Sand Drain Spacing (ft)	No. of Data	Average Horizontal Permeability (ft/min x 10^{-6})
Comparison of Data for 14-ft Sand Drain Spacing			
A	14	6	0.38[a]
B	14	2	0.12[a]
C	14	2	0.50[a]
		7	0.60[b]
Comparison of Displacement and Nondisplacement Sand Drains			
C	20[c]	5	0.74[a]
		15	1.72[b]
D	20[d]	2	1.16[a]
		7	1.12[b]
Comparison of Fungaroli with Davis and Poulos Methods of Analysis			
B	—[e]	2	34[b,f] 26[b,f]
		4	180[a,f] 30[a,g]
C	—[e]	9	1,120[a,f] 70[a,g]

[a]From settlement platform data.
[b]From piezometer data.
[c]Nondisplacement sand drains.
[d]Displacement sand drains.
[e]Non-sand drain areas.
[f]Fungaroli method of analysis.
[g]Davis and Poulos method of analysis.

is that the area B soils have a higher preconsolida-
tion, about 2 tsf compared with about 0.5 tsf for
the other areas. This preconsolidation could have an
effect on horizontal permeability, but it is doubt-
ful if it is of any significance compared with the
natural variation in the horizontal permeability
discussed previously. The reason for this statement
is that the imposed loadings in some sections of
areas A and D were of a magnitude of 1.8 tsf and
consequently resulted in total pressures of up to
2.0 tsf, the preconsolidation pressure for area B.
If maximum pressure had a major effect on horizontal
permeability, the permeabilities of these areas
should all have been relatively close. Consequently
the difference in effective horizontal permeability
for area B compared with the other three areas must
be due to depositional or other conditions rather
than to the difference in preconsolidation pressure.

Displacement Versus Nondisplacement Sand Drains

The calculated horizontal permeability data provide
a means of evaluating the relative efficiency of
displacement and nondisplacement sand drains. The
horizontal permeability test drains plotted in Fig-
ure 8 show that the nondisplacement sand drain hori-
zontal permeability is one order of magnitude higher
than that for the displacement sand drains. The data
in Figure 11 and Table 3 indicate that the 20-ft
drain spacing for area C where nondisplacement sand
drains were used had essentially the same permeabil-
ity as did displacement sand drains with the same
spacing in area D. Permeabilities for both driven-
and wash-type sand drains are one order of magnitude
lower than that for the lowest test drain shown in
Figure 8.

The wash drain used for the tests (2) shown in
Figure 8 was constructed by jetting a pipe down and
then backfilling with sand. The production nondis-
placement sand drain was constructed by a different
method, as noted previously. The different construc-
tion methods employed could possibly explain part of
the difference between the permeabilities calculated
for the two types of nondisplacement sand drains.
However, the difference between the test and produc-
tion displacement sand drains cannot be explained on
this basis because the construction of both types
was essentially the same. It is believed that there
is another factor causing the difference. This is
discussed later.

Non-Sand Drain Areas

Analysis of the non-sand drain calculated horizontal
permeability data provides some interesting results.
The calculated horizontal permeabilities for the
non-sand drain areas are at least one to two orders
of magnitude greater than that for any of the sand
drain areas. The most logical explanation of this
difference is the disturbance effect on the soil
permeability resulting from the sand drain con-
struction.

Based on the permeability data for the two test
sand drains reported by Casagrande and Poulos (2),
the calculated permeabilities for these non-sand
drain areas provide reasonable results and indicate
that the theoretical methods used to calculate the
permeabilities appear to be valid. Both methods
(6,7) used to calculate the horizontal permeability
based on the field settlement and piezometer data
are based on horizontal drainage only. This condi-
tion is reasonable for this varved clay deposit
because of the very high ratio of horizontal to
vertical permeability noted previously (2).

A comparison of the results of the two methods of
analysis was made (Table 3) and is of interest.
Results for the two methods are fairly close based
on the piezometer data. Horizontal permeability
results for the settlement platform data using the
Fungaroli method are about one order of magnitude
greater than results obtained using the Davis and
Poulos method. Laboratory permeability test data on
prepared samples of silts and fine sands (8) were
used to help evaluate this difference in results.
Based on past visual examinations of varved clay
samples it was judged that a high percentage of the
varves could contain 1 to 5 percent silt or fine
sand and silts. The permeability results for this 1
to 5 percent content of (a) a coarse silt, (b) a
fine sand and coarse silt, and (c) a fine sand were
calculated from the Burmister data and plotted in
Figure 12 along with the calculated permeabilities
for the non-sand drain areas. This comparison and a
comparison of the other permeability data shown in
Figures 8 and 11 indicate that the field permeabil-
ity data calculated by use of the Davis and Poulos
method appear to be the more reasonable.

A detailed review of the theoretical background
of these two methods of analysis seems to be needed
because there is no obvious reason for this differ-
ence. One possible reason for the difference in
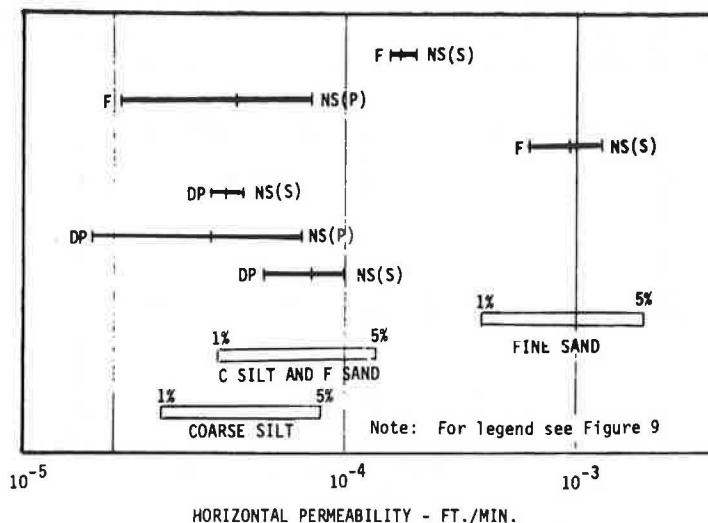results obtained using the two methods of analysis

FIGURE 12 Field permeability data for non-sand drain areas.

is the boundary drainage conditions. The Fungaroli method assumes the soil area beyond the limits of soil consolidation swells in volume equal to the volume of soil consolidation. The Davis and Poulos method assumes the soil area beyond the limits of soil consolidation is free draining.

The calculated permeabilities for these two non-sand drained areas equal or exceed the highest field and laboratory permeability tests as do the results for the two test sand drains shown in Figure 8. These two observations indicate that for varved clay deposits small-scale laboratory and field permeability tests generally will result in calculated permeabilities that are significantly less than the true effective horizontal permeabilities of the deposit.

Effect of Sand Drain Spacing

The range of calculated field horizontal permeabilities for all the sand drain areas is of two orders of magnitude and this range can be attributed at least in part to the normal variability in the in situ permeability shown in Figure 8 and discussed previously. There is another possible contributing factor, the spacing of sand drains. The relationship between the average calculated horizontal permeability and the sand drain spacing is shown in Figure 13. These data indicate that the closer the sand drain spacing, the lower the calculated horizontal permeability. From these data it appears that smear or disturbance from the driving of the sand drains has a significant effect on the horizontal permeability and the dependent rate of consolidation. A similar trend for sand drains in tidal marsh deposits has been noted (9).

The calculated horizontal permeabilities for the non-sand drain areas are of one to two orders of magnitude greater than the calculated horizontal permeabilities for the sand drain areas. This condition may be the result of the lack of any disturbance or smear of the more permeable portion of the varve layers in the non-sand drain areas.

The data presented in the two preceding paragraphs give strong evidence that the use of sand drains in varved clay deposits greatly reduces the effective horizontal permeability of the deposit. The reduction in permeability due to the use of sand drains in tidal marsh deposits (9) was much less.

This summary of field permeability data provides a guide for the calculation of settlement rates for future construction projects in the varved clays of these areas of the Hackensack meadowlands. Laboratory or small-scale field permeability tests can provide a basis for estimating consolidation rates,

but a significant number of tests, at least 6 to 12, are necessary to develop the range of permeability conditions.

Figure 11 also provides a guide for the choice of design permeability values. The mid-to-lower portion of the permeability range is applicable for sand drains; the lower portion should be used for closely spaced drains, and the midportion used for more widely spaced drains. The upper portion of the permeability range should be applicable for non-sand drain areas.

Depending on comparative soil types and index properties, these data may provide useful guidance for other areas containing varved clays within both the Hackensack meadowlands and other glacial lake deposits.

CONCLUSIONS

Following are the conclusions derived from the comparison of horizontal permeability of the varved clay deposit calculated from field settlement and piezometer data.

The wide range in horizontal permeabilities derived from small-scale laboratory and field tests was confirmed by the embankment piezometer data.

The actual embankment settlement rates indicate that the effective horizontal permeability for the sand drain areas falls in the lower half of the range of results obtained from the small-scale laboratory and field permeability tests.

There is a significant difference in the horizontal permeability of area B compared with areas A, C, and D that is apparently due to causes other than the difference in preconsolidation pressure.

The type of nondisplacement sand drain used showed no significant improvement in efficiency over the standard displacement sand drain in this varved clay deposit.

These data give strong evidence that the use of sand drains in varved clays causes a significant reduction in the horizontal permeability of the soil. It also has been observed that the closer the sand drain spacing, the greater the reduction in horizontal permeability. These conclusions show the significant disturbance effect that sand drains can have on varved clay permeability.

The Poulos-Davis method of determining settlement rate appears to provide more realistic results than the Fungaroli method for this varved clay deposit, when both methods are based on consolidation resulting from horizontal drainage only.

The effective horizontal permeability, based on the data from the non-sand drain areas and on the single jetted test drain described by Casagrande and
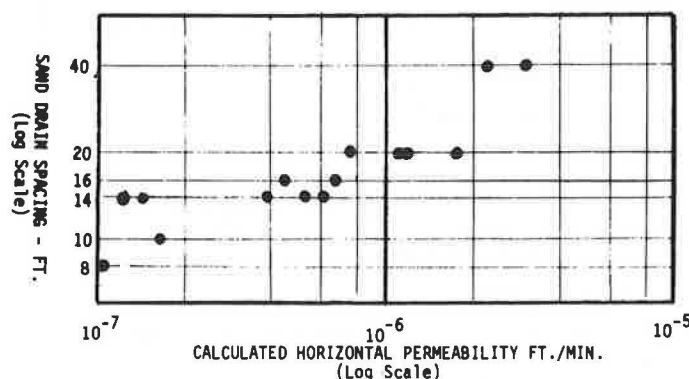

FIGURE 13 Calculated horizontal permeability versus sand drain spacing.

Poulos, seems to be significantly greater than in-
dicated by most horizontal permeability data deter-
mined by small-scale laboratory and field permeabil-
ity tests.

ACKNOWLEDGMENTS

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Pedotechnical Aspects of Organic Soil Classification and Interpretation

GILBERT WILSON

ABSTRACT

Exploration and classification of organic
soils in transportation research is done
primarily to predict performance and impacts
of construction activities. In the pre-
liminary stages, published maps are included
in the data base. There is a continuing need
for improved methods of interpreting surveys
performed by mapping agencies as the state
of their art develops. For Canadian soil
survey applications, the pedotechnical set-
ting sheet has been proposed. The setting
sheet is a modular framework in which soils
and landscape data pertinent to engineering
are presented graphically. The site-specific
appearance of the mapping unit data has
resulted in slow acceptance. This question
is addressed using the case history of a
geotechnical site appraisal for embankment
construction over highly organic soils. A
feel for soil behavior is developed as the
site investigation proceeds. In retrospect,
it is seen that the graphic data, which are
superimposed on the setting sheet back-
ground, pertain to the central concept of
the mapping unit, and they are presented in
this form in order to pass on the feel for
soil behavior to others, with minimum effort
and cost.

In transportation research the interest in classifi-
cation of highly organic soils stems from the need
to better predict performance and impacts of con-
struction (1). For site appraisals, published maps
and surveys may represent the only data base and
interpretations of mapping units are provided in
many areas (2). A continuing need exists for im-
proved methods of classification and interpretation.
For geotechnical applications, improvement should be
such that a better feel for the soils mapped can be
developed (3). The practical uses and limitations of
existing classification schemes for organic soils
are discussed by tracing the stages of a typical but
difficult site investigation. Stemming from this is
a proposal to make more effective use of this type
of site experience and to assure that the informa-
tion gained is made available for subsequent appli-
cation.