DEVELOPMENT OF
A RATIONAL METHOD TO DESIGN
WICK DRAIN SYSTEMS

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Final Report

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DEVELOPMENT OF A RATIONAL METHOD TO DESIGN WICK DRAIN SYSTEMS(a)

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Introduction

Field experience indicates that wick drains installed vertically in grid fashion do not consistently result in the required degree of consolidation, under construction loading, in the time established in design. Such deviations are often related to variations in soil characteristics that are not fully identified due to limitations of soils investigation and testing. It was recognized that pore pressure is induced during the mandrel installation of drains; however, it was assumed that such pressures dissipate rapidly and was omitted in developing radial drainage theory currently used to design wick drain installations. Research funded by the University Transportation Research Center, Region II, was implemented to Investigate the validity of the assumption.

The initial research grant to Rutgers University was used to determine the nature and extent of pore pressure induced during wick drain installation, using a prototype model of insensitive clay of low plasticity. A second grant involved research at a New York State Department of Transportation (NYSDOT) construction site to verify the laboratory findings.

(a)Based on a May 1997 dissertation by Richard E. Landau submitted to Rutgers University in partial fulfillment of Ph.D. requirements(23).

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Vertical Drains-Theory and Practice

The application of vertical drains to expedite consolidation of saturated compressible soils by radial drainage was patented by Moran(1) in 1926. Porter(2) pioneered the use of sand columns as drains in the early 1930's at the time that prefabricated ribbon shaped 4"x1/8" cardboard "wick" drains were being developed by Kjellman(3) in Sweden. Using Darcy's Law(4) of fluid flow as well as assumptions formulated by Terzaghi(5) in developing soil consolidation theory for one dimensional flow, Rendulic(6) developed a mathematical solution for the time rate of soil consolidation for two dimensional radial drainage from a cylindrical soil mass to a concentric circular drain. Carillo(7) later developed a solution for consolidation with concurrent vertical and radial flow. Barron(8) published parametric curves applicable to equally spaced circular drains in square and triangular grids, and included reduced soil permeability in a remolded or smeared zone of soil displaced to the drain periphery, as occurs when drains are installed by mandrel. Barron also provided means to evaluate the influence of the permeability of the drain material on the time rate of consolidation. Kjellman(9) published parametric curves applicable to circular drains spaced in a square pattern, and applied these to the design of 4" wicks which he established as being equivalent to a 2" diameter drain.

The wick developed by Kjellman was not widely used as the low wet strength of the cardboard subjected the wick to tearing, which made installation unreliable. Wicks were subsequently reconfigured as a result of the development of plastics and geotextiles which are not adversely affected by water. Since the 1970's wicks in commercial use generally consisted of a corrugated or dimpled plastic core to guide water flow, covered by a geotextile filter fabric to prevent the passage of soil particles, as shown in Fig. 1. Although accepted wick configurations vary, engineers have found that the 2" equivalent drain diameter applied by Kjellman to be reasonably valid for any 4" wide ribbon shaped wick, despite that fact that values generally ranging from 1.5" to 2.5" in diameter have been used as described by Suits(10) and Long(11).

Prior to the development of non-displacement jetting and augering(12)(13) methods, which improved sand drain performance, sand drains were installed by driving a pipe or "mandrel" to form the drain cavity, which is the method used for wick installation. In mandrel driven sand drains, the mandrel is driven to the required depth, and the drain is formed by introducing sand to fill and support the soil cavity formed on mandrel withdrawal. In the case of wick drains, the wick material is carried with the mandrel in its advance, and left in place on mandrel withdrawal, such that the collapse of the unsupported soil cavity formed on mandrel withdrawal permits unobstructed radial drainage from the consolidating soil to the wick.

Mandrels used to install sand drains are commonly 12" to 24" in diameter, with air pressure applied to the upper surface of the sand to insure flow into the soil cavity on mandrel withdrawal, and the diameter of the completed sand drain reflects the cross-sectional area of the mandrel used. This contrasts sharply with the wicks, where the shape of the drain is fixed, usually 4" wide, and the mandrel cross-sectional area of 8 to 12sq.in. is 15 to 25 or more times that of the wick to obtain the rigidity needed for its linear advance to into the soil. Nevertheless, equipment used in wick installation is lighter and less costly to operate than a mandrel sand drain rig. While theory indicates 4 times as many wick drains are required in a given area to be as effective as a 12"diameter sand drains(14), the fact that wick installation costs about 1/10th that of driven sand drains results in wicks being on the order of 2.5 times more cost-effective.

Wick drain and driven sand drain grid designs have at times required substantially longer periods of time to achieve 90% of primary consolidation in the field than radial drainage theory would indicate. The poor field performance of driven sand drains has been ascribed to the volume of soil displaced by the 12" dia. mandrel used for driven drains. While theory indicates that both wick and sand drain mandrels develop a Smear Ratio(smear zone diameter to effective wick drain diameter) of 1.5 and 2, the adverse effect on consolidation rate as well as soil strength may be less for wicks as its mandrel cross-section is about 1/10th the area of that used in driving sand drains. It is noted that slope instability, which has occurred in embankments where driven sand drains(15) have been used, has not been a factor in mandrel driven wick installations.

A variety of explanatuions have been provided for the unexpected differences between wick drain design expectations and performance in the field. The variability of in situ conditions that are not fully determined as a result of the practical limitations of soil sampling and testing is always a factor. Clogging of the geotextile filter of the wick may affect the proper field performance of wicks, where the potential for geotextile clogging, as described by Holtz(16),.was not considered. Although a report by Richardson(17) that particle migration that causes clogging normally does not occur in soils with a Plasticity Index of less than 15, Indraratna(18) used a mathematical model applying back-pressure to simulate clogging at the soil-wick interface to explain the poor performance of wick drains at a research site involving Marine Clay with a Plasticity Index in excess of 20. Whereas time related clogging due to particle migration may adversely effect the performance of wick installations, it is of interest to note that clogging of clean sand, which is not as effective a filter as wick drain geotextiles, is not a factor in the progress of consolidation of sand drain installations(19).

Basis for Proposed Research

Although many reasons are available to designers to explain unforeseen discrepancies between design expectations for the time to achieve 90% of primary consolidation and the field performance of wick grid installations, to date none have related to possible deficiencies in raial drainage theory as applied to accepted design practice. The need for a review of accepted theory is suggested by an evaluation of research data presented by Akagi(20) on mandrel driven sand drains, which shows time dependent dissipation of installation induced pore pressure is not accompanied by water flow. This finding is contrary to Darcy's Law which on which radial drainage theory and wick drain design practice is based. Radial drainage theory also assumes pore pressure induced by the mandrel installation of drains dissipate rapidly and is ignored in the evaluation of time related radial flow to a drain(8).

Soderberg(21) and Hagerty(22) had attempted to define pore pressure profiles induced by pile driving; however, the results were not related to intallations where a drain is at the site of induced pressure. As such, it was decided to investigate the nature and extent of mandrel induced pressures on a prototype model, as a step toward expanding the evaluation of drains using the model developed by Carillo and Barron.

Laboratory Model, Equipment, and Testing

Clay used to construct the prototype model was supplied to Rutgers University by the NYSDOT from a construction site in Buffalo, New York. As the clay was insensitive. its characteristics were substantially unaltered as a result of remolding involved in forming the laboratory research model. The range of in situ characteristics determined by laboratory tests on "undisturbed" samples are presented in TABLE I.

TABLE I
In Situ Soil Characteristics

NYSDOT Boring No.	Sample Depth ft.	Atterberg Limits		Dry Density PCf	Water Content %	Compression Index C	Void Ratio e
		LL	PL				
UDNB–3	21	33.2	19.7	89	34.5	0.28	0.85
	29	34.4	19.1	84	38.3	0.40	0.98
	37	44.8	21.2	74	48.3	0.53	1.25
	41	31.9	17.2	79	42.7	0.57	1.11
	45	24.3	14.7	84	38.3	0.45	0.98
UDNB-8	21	35.3	19.8	89	34.1	0.29	0.96
	33	36.6	20.8	78	43.8	0.50	1.11
	37	37.6	18.5	78	44.9	0.57	1.15
	41	31.4	18.5	86	36.7	0.41	0.94
	49	35.4	18.0	81	41.8	0.43	1.09

A laboratory model 4′x4' in area was proposed for research, as the installation of a central wick would reflect the 4'c-c square grid spacing that NYSDOT planned to use in construction. The model was to be housed in a steel frame and the "end effects" were unknown. While the depth of the model was not critical to the investigation of the radial distribution of pore pressure, it was decided to use a 13" depth to minimize the unknown "end effects" of the upper and lower steel plates used to confine the soil model, as shown in Fig. 2. Based on an evaluation of test results in TABLE I, it was decided to form the model at a 40% moisture content by placing 13 successive 1" layers of saturated clay in the following manner:

a. A batch of approximately 160lbs. of clay was placed in a large galvanized metal pan and samples were taken to determine its moisture content. Each batch was covered with plastic and stored in a "moist room" to avoid change in water content while awaiting the moisture content test results.

b. Based on the results in a., water was added and manually kneaded into each batch to produce saturated clay having a 40% moisture content. The soil moisture content was again checked and the degree of saturation determined. Water was added as necessary to closely produce 100% saturation in each clay batch.

C. The 4'x 4' movable steel base plate of the model frame was initially positioned 1" below the upper flanges of the steel frame, Fig. 2. The first batch of clay was placed and screeded to form the first 1" layer, which became the lowermost in the clay model. The base plate was lowered in 1" increments, and each successive batch of clay was screeded until the 13" deep clay model was formed.

The miniature piezometer shown in Fig. 3 was developed for this research to minimize the extent to permit closely spaced pore pressure observations. Piezometers were calibrated in water over a 0 to 30psi pressure range. The piezometers were then tested in soil, where it was found that about 50% did not function due to breaks in delicate wiring as well as clogging of the 22gauge tube as a result of being inserted into the clay soil. As a result of its 50% mortality rate, a 4"dia. mandrel was selected for laboratory wick installation. The use of a circular mandrel with a cross-sectional area similar to that of commercial mandrels, permitted radial piezometer redundancy along orthogonal axes of the model, as shown in Fig. 4.

A computer program was written to control the IBM-Hewlett Packard data acquisition system shown in Fig. 5A, which enabled simultaneous observation and recording of data during the sequential scanning of each of 26 piezometers used to monitor pressures at the mid-depth of the clay model. The soft plastic bladder used for load application was positioned at the upper surface of the clay model and constrained by an overlying steel plate within the peripheral steel housing, as shown in Fig. 2. Twenty six piezometers were inserted through entry points in the base plate, with a partial printout of data after piezometer insertion shown in Fig. 5B. Connections at piezometers with unusually high or low reading were checked and, where corrections were made when possible. The bladder was pressurized at 5psi and the piezometers were found to be reasonably sensitive to pore pressure changes, and fully reflected the 5psi test load within 5 minutes after its application. There was no water leakage from the model under the 5psi load.

The laboratory test involved recording changes in pore pressure at the depth monitored during and after wick installation at the center of the model. A plywood cap with a 14" length of wick attached, was positioned at the lead end of a hollow mandrel, with the wick extending through the mandrel. The mandrel and the loosely fitted cap was set at the lower surface of the clay model through an opening in the steel base plate. With the bladder pressurized at 5psi, the mandrel was jacked through the soil for a distance of about 12.5" to avoid damage to the bladder 13" above the model base. Insertion took about 1.5 minutes as the mandrel alignment needed to be adjusted as a result of the arcuate stroke of the automobile jack used to advance it through the clay. Bladder pressure was reduced to zero immediately after the full mandrel advance, to avoid having the cap and wick pushed into the unsupported cavity formed by mandrel withdrawal. Visual inspection of the cavity through the entry point at the lower base plate indicated that at least the low end of the cavity had collapsed. The fact that only a few inches of wick extended below the clay at the base plate suggested it extended fully through the model as shown in Fig. 2. The wick was trimmed flush with base plate at the entry, and the entry was covered with a vented cap after adding sand to fill the void at the outlet end of the wick. The bladder was again inflated at 5psi, which was maintained for about 2 hours to insure full soil contact with the wick developed. Water flowed continuously through the vented cap at the wick outlet for the full time the 5psi load was maintained, with minor leakage occurring at the perimeter of the steel base plate. Both flow and leakage stopped abruptly when pressure at the clay surface was again reduced to zero.

Piezometers were scanned continuously from the start of mandrel advance until about 2 hours after mandrel removal. Data was acquired afterward at a diminishing frequency until the induced pore pressures fully dissipated. Of the 26 piezometers installed, 15 functioned substantially during the full time of research data acquisition. Of the 11 piezometers which did not function, 4 were located within the annulus of soil displaced as a result of mandrel advance, 4 failed due to clogging, and 3 failed as a result of breaks in electrical wiring and soldered connections.

Data recorded at the completion of mandrel advance, as plotted in Fig. 6A along 4 radial positions on orthogonal axes, consistently shows that peak pore pressures occurred beyond the annulus of soil displaced by the mandrel. Peak pressures that developed at the periphery of the model were considered "end effects" which likely related to both the fit of the bladder during its initial pressurization, and rigidity of the steel frame holding the model. It is of interest to note that Fig. 6B, which is a uniaxial plot of data in Fig. 6A without the "end effects", suggests that the distribution of induced pore pressure is independent of the peak pore pressure. Data obtained after mandrel withdrawal is plotted in Fig. 7, which shows that as much as 6 days was required for induced pore pressure to fully dissipate.

Evaluation of Laboratory Data

The evaluation of research data is based on the following assumptions, which reflect accepted design practice as well as the results of laboratory testing and field experience:

i. The design of wick drain grids is based on accepted radial drainage theory applied to circular drains, using a 2"dia. sand drain to reflect a 4"x1/8" wick.

ii. A mandrel with a cross-sectional area of 8 to 12 sq.in. to place wicks 'induces a Smear Ratio (effective annular diameter of the smear zone to the effective wick diameter) of approximately 2.

iii. Flow resistance in the wick is not a consideration in the dissipation of installation induced pore pressure, as soil settlement does not accompany its dissipation.

iv. As coefficients of vertical consolidation for the the laboratory model and insensitive isotropic soil at the field test site used to form the model were were found to be the same, the coefficients of radial consolidation were assumed to equal the vertical coefficient, and the coefficients of vertical and radial permeability were also assumed to be equal.

V. The coefficient of consolidation for the clay soil was found to be on the order of 0.2 ft.sq/day for normally loaded and remolded soil, and the in situ vertical and radial coefficients of permeability were also assumed to be equal.

vi. The 4’x4' laboratory prototype model with a single wick drain at the center was taken to be equivalent to a 4’x 4' square grid wick spacing in the field.

The profiles in Fig. 6A reflect pore pressures induced along orthogonal axes as a result of mandrel advance during wick installation. Radial symmetry permitted redundant use of data to complete the profile along orthogonal axes of the model; however, no data was obtained in the zone of soil displacement at the mandrel periphery as all piezometers malfunctioned.

The abrupt pore pressure increase to 4psi in the area adjacent to the steel frame is considered an "end effect" in the plastic clay as a result of its displacement in the vicinity of the steel frame, as described earlier. Ignoring data related to the end effect, the data in Fig. 6A is presented uniaxially in Fig. 6B in terms Offset and Pore Pressure Ratios, based on a mandrel radius of 2" and 5.5psi total stress at the monitoring depth, respectively. Values of Offset and Pore Pressure Ratio for the piezometers within the zone of influence of wick installation, are listed in TABLE ll.

TABLE II
Laboratory Offset and Pore Pressure Ratios

Piezometer	4	9	14	17	40	49	54	59
Max. Pore Pressure, psi	6.0	1.8	6.2	5.0	5.9	4.0	4.8	5.3
Pore Pressure Ratio	1.1	0.3	1.1	0.9	1.1	0.7	0.9	1.0
Offset, Inches	8.3	13.8	7.8	6.3	5.9	2.0	4.4	6.7
Offset Ratio	4.2	6.9	3.9	3.2	3.0	1.0	2.2	3.4

Peak pore pressures within an Offset Ratio of 5 relate to Pore Pressure Ratios of 0.9 or more, as shown in Fig. 6B. Values of induced pore pressure that may inhibit drainage to the wick occur within a zone of soil that extends to no more than 12" from the point of installation, which corresponds to a limiting Offset Ratio of 6.

A plot of residual pore pressure against logarithm of time after mandrel removal and wick installation is presented in Fig. 7. It was found that pressures at piezometers 40 and 49, which are at an Offset Ratio of 3 or less, increased by 10% to 20% on mandrel removal and soil collapse. Pressures at piezometers at Offset Ratios greater than 3 are substantially'unaffected by soil collapse. Piezometers 40, 49, and 59, are representative of those positioned along Axis A, in a plane perpendicular to the 4" face of the wick, exhibit a 50% to 80% or more drop in pore pressure within 15 minutes after mandrel removal,whereas piezometers 17 and 55, which are respectively on orthogonal Axis B and in a plane at a 45 skew to the face of the wick, show pressure drops of 10% to 30% in that same time.

Pore pressure dissipation, as shown in Fig. 7, is directly related to the logarithm of time within about 30 minutes after mandrel removal and soil collapse, and that full dissipation took place within about 6 days (9,000 minutes). It is not reasonable to use soil consolidation theory cannot to evaluate the pore pressure dissipation as no drainage occurred during the 6 days. Furthermore, a 0.2ft.sq/day, coefficient of consolidation indicates that a pore pressure drop of 10% or less would occur a 15 minute interval and it would take an infinite time for pore pressure to fully dissipate.

The need to evaluate the dissipation of induced pore pressure relates to the fact that its peak values occur in the annulus of soil immediately adjacent to the drain. With pore pressure induced by embankment loading being additive(20) to that induced by driven drain installation, the initially high pore pressure at the wick will obstruct drainage from the zone of soil beyond the peak pore pressure zone. As stated earlier, the zone of peak pore pressure occurs in soil within a 10" radius around the wick axis (Offset Ratio of 5) where the pressure gradient for drainage to the wick remains positive at all times.

The initial portions of the Pore Pressure-Time curves to the end of its rapid drop in pressure, as seen in Fig. 7, is termed "initial dissipation", and the slow reduction in pressure thereafter is termed "residual dissipation". As seen in Fig. 6A, the induced pore at piezometer 14 peaked at a value 6.2psi and piezometer 59 peaked at 5.3psi, which are about 7.8" and 8.6" from the wick, respectively. In each instance initial dissipation occurred in 15 minutes or less as shown in Fig. 7. Piezometers 40 and 49, which are 3.7" and 4.5" from the wick, respectively, have divergent rates of pressure dissipation. In contrast to this, piezometers 49 and 55, which are each 5" from the wick, have the same peak pressures and rates of pressure dissipation. It appears that peak pore pressures induced cannot be correlated with offset distances; however, Fig. 6B suggests that the pore pressure profile beyond the peaks are similar and independent of the maximum pressure induced. Fig. 7 suggests that the pore pressure at the end of initial dissipation as well as rate of residual dissipation may be inversely related to the maximum pore pressure induced at any point.

The magnitude and rate of pore pressure dissipation is found to be greater at piezometers positioned in the plane of the wick minor axis as compared to piezometer 17 which is located on the wick major axis. Finding that initial pore pressure dissipation at piezometer 17 took about 30 minutes while less than 15 minutes was needed at 40, 49, and 55 suggests that stress relaxation may be constrained in the plane of the wick major axis, and dissipation is more rapid in the soil along the 4" width of the wick.

Inspection of the surface of the clay model after the completion of loading and bladder removal, showed two major areas of distortion, as shown in Fig. 8. The clay surface at the wick was found to be on the order of 1" higher than the soil beyond the wick, while clay at the steel frame varied from 1.5" to 2.5" above the adjacent soil. Upward displacement of clay at the wick reflects the capped mandrel initially displacing soil in the direction of its advance, which was then displaced laterally as advance continued. Upward movement at the peripheral edges of the model likely resulted from the initially flat periphery of the bladder being pulled inward and becoming rounded as it inflated and pressurized. Load discontinuity and local overstress likely accompanied the intermediate stage of rounding of the bladder at the model periphery, which caused upward soil displacement to fill the void between the rounded bladder periphery and the steel frame. The continued pressurization caused the bladder to expand laterally to the steel frame, confining clay which had displaced and prevented its further upward displacement. At the completion of its expansion, the bladder filled the space between the steel loading plate, the modified clay surface, and the walls of the steel frame, as shown in Fig. 2.

Field Testing

Field research was performed in conjunction with NYSDOT at the site of the Tifft Street relocation over the Conrail tracks in Buffalo, New **York,** Fig.8, where wick drains were used to expedite settlement of compressible clay underlying bridge approach embankments. The field testing was done after site regrading at four areas segmented within locations scheduled for wick drain installations. Areas D-1 and D-2 involved wick drains spaced 6'c-c, and areas D-3 and D-4 had wicks spaced 4'c-c.

The layout of wick and piezometer installation locations at the ground surface is shown in the insert of Fig. 8. The piezometers were positioned in a plane transverse to the face of the nearest wick based on the laboratory finding that pore pressure dissipation was more efficient in positions facing the 4" width of the wick as compared to positions aligned with its narrow dimension.

The field monitoring level for induced pressure was set in the clay stratum at a depth of 30' to 35' below the ground surface, as shown in Fig. 9. Vibrating wire piezometers were installed at the monitoring depth by means of a hollow stem auger. The relative position of each piezometer at the monitoring depth was estimated with respect to its point of installation at the ground surface by evaluating the alignment of the auger hollow stem which was established by inclinometer. Each piezometer was surrounded with sand at the depth monitored, and the upper level of the sand was sealed to insure that pressures at the piezometer reflected pore pressure in the soil at that level. All of the piezometers in a test area were in place prior to the start of wick installation.

Wick installation was done with a self-propelled mobile rig which holds a reel of prefabricated wick drain material and supports a hollow mandrel within a rigidly mounted track to guide its advance into and withdrawal from the soil(16). Wick material is fed from the reel to the top of the mandrel and then downward through the hollow and is exposed at the tip of the mandrel at ground surface. A suitable anchor is attached to the exposed end of the wick which keeps it in place at the lead end of the mandrel. Mandrel advance into the soil pushes the anchor into the soil, which is turn pulls the wick drain material from its supply on the reel(16). Soil displaced ahead of the mandrel is positioned along its periphery as its advance progresses. Completion of mandrel advance fixes the anchored wick in the soil ahead of the mandrel where it remains fixed during mandrel withdrawal. In situ stresses cause the soil cavity formed during mandrel withdrawal to collapse and hold the wick in position in the required drain grid.

An angularly shaped mandrel with a cross-sectional area of about 12sq.in. was used to install the field test wicks. The mandrel was advanced through vertically augered holes which were used to guide the wick installation alignment to the monitoring depth. Augering was limited to a depth of 25' to insure that pore pressures at the 35' monitoring depth reflected soil displacement during mandrel advance. Guide hole alignments measured by inclinometer were extrapolated to estimate wick positions at the monitoring depth. It is noted that all wicks were positioned so as to have adjacent piezometers transverse to the face of the wick for drainage efficiency as well as to avoid introducing wick orientation as a variable in the evaluation of the recorded pore pressures. Wick production in the field averaged about 30' per minute.

Accurate information on the location of piezometers to wicks was neededto check the induced pore pressure profile found in laboratory research, as shown in Fig. 6. Despite efforts to install piezometers and wicks vertically in the field, estimates of offsets at the depth of monitoring in Area D-3 were found to be in error by up to 5", as shown in Fig. 10. However, an error of +/-6" or more in wick and/or piezometer alignments occurred in one instance where a wick installed at a ground surface piezometer offset of 12" sheared the piezometer cable at a level of about 10' above the monitoring depth.

Evaluation of Field Data

Plots of pore pressures for wicks installed on May 23 and May 24 are shown in Fig. 11. No attempt was made to develop a profile of induced pore pressure as the installation procedure described earlier did not result in a sufficiently accurate determination of wick to piezometer offsets at the monitoring depth. However, field research data permitted a comparison with laboratory findings with respect to:

i. Magnitude of pore pressures induced as a result of wick installation; and

ii. Time required for the full dissipation of pore pressure induced by wick installation.

A summary of the results of an evaluation of field data presented in Fig. 11 are listed in TABLE III.

TABLE III
Field Pore Pressure Ratios and Dissipation

Test Area	D1	D2	D3	D4
Sq. Grid Wick Drain Spacing	6'	6'	4'	4'
Peak Pore Pressure, psi	19	20	16	22
Peak Pore Pressure Ratio	1.1	1.2	0.9	1.2
Time for 80% Dissipation, hrs.	2	1/2	1	1/4

Peak Pore Pressure Ratios listed in TABLE III range to a maximum of 1.2, which are consistent with laboratory research observations; however, the time required for 80% pore pressure dissipation in the field diverges from laboratory values by as much as a factor of 8. Although the cause, or causes, of divergence in time required for pore pressure dissipation was not identified, it may relate to the the fact that l00psi air jetting was used to advance the mandrel beyond the limiting. preaugering depth· 10' above the monitoring level. It is likely that air became entrapped on mandrel removal when its pressure reduced to values less than active soil stress. As such, the time range presented in TABLE I11 for 80% pore pressure dissipation may reflect the rate of pressure reduction in entrapped air pressure which in effect sustains the pore pressure of water in the soil.

The following describes observations made as a result of an evaluation of data compiled at the four test areas at the NYSDOT field research site:

Area D-1

Wicks installed 6'c-c in Area D-1 on May 19 induced a maximum pore pressure of 8psi, which reduced to 2psi, a reduction of 75%, in about an hour. Installations completed on May 23, as shown in Fig. 11, induced pore pressures of up to 19psi, with 80% dissipation occurring in approximately 2 hours.

Area D-2

As in the case of Area D-1, pore pressures induced by wicks installed 6'c-c on May 23 ranged to a maximum of 20psi, as shown in Fig. 11. Induced pore pressure was found to dissipate 80% in about an 1/2 hour.

Area D-3

Wicks installed in Area D-3 May 18 at 4'c-c induced pressures of 6psi as a maximum, a Pore Pressure Ratio of 0.3, and dissipated about 80% in 1/4 hour. An additional wick drain installed May 24 produced a maximum pore pressure of 16psi, as shown in Fig. 11, requiring about 1 hour for 80% pressure dissipation.

Area D-4

Wicks installed May 18 at a 4'c-c spacing induced a peak pressure of up to 3psi, requiring in excess of 1 hour for 80% dissipation. This was not evaluated as 3psi represents a Pore Pressure Ratio of less than 0.3, which is the reliability limit established by laboratory testing. Wicks installed May 24 induced peak pore pressures of 17psi and 22psi, and required up to 1/2 hour for 80% dissipation.

The comparison of pore pressure observations was based on a range of Pore Pressure Ratios induced by installation for a total stress of 18psi at the monitoring depth in the field as compared to 5.5psi used in the laboratory. As in the laboratory, time for full dissipation of "residual" pore pressure in the field was considerably longer than the time for dissipating 80% of the "initial" pore pressures. As field data acquisition was intermittent after May 24, time for full pressure dissipation required extrapolation. Nevertheless, the 1/4 and 3/4 hours needed to dissipate 80% of induced pressure in field Test Areas D-1 through D-4 is reasonably consistent with laboratory findings.

Extrapolation of field data to determine the time for dissipation of residual pressures induced in the field was based on the laboratory finding that dissipation relates to the logarithm of time and is independent of magnitude of pore pressure induced. It was accordingly estimated that pore pressure was dissipated in no more than 8 days at the field test sites, which is in reasonable agreement with the 6 days established in the laboratory research program.

Plots of field data related to roadway embankment construction as well as time related settlement under fill loading at a typical test area are provided in Fig. 12. Data related to pore pressure increase during fill placement and its subsequent dissipation is presented in Fig. 13. A detailed evaluation of the information is beyond the scope of the field research; however, a cursory review of the data based on the NYSDOT presentation of data indicating the effective time of full load placement corresponds to the date of embankment completion, suggests a 20 to 30 day delay in the field performance of wick drains as compared to the time established by accepted theory.

Conclusions

The following conclusions were reached based on the results of laboratory and field research performed at Rutgers University and at field test sites in conjunction with with the NYSDOT:

a. Pore pressure induced by mandrel advance for wick installation in compressible soil does not dissipate immediately on mandrel withdrawal and cavity collapse.

b. Dissipation of mandrel induced pore pressure is time dependent, taking about 6 days to occur in the laboratory and 8 days in the field for the insensitive soil of low plasticity tested.

C. Dissipation of pore pressure induced by wick installation after mandrel removal and prior to soil loading occurs without soil drainage or settlement.

d. The pore pressure profile for the laboratory soil model peaked at 5psi or more at an Offset Ratio between about 3 and 5. Peak pore pressures which occurred within 4" of the rigid frame used in laboratory research were disregarded as being effects of the method of loading and the finite lateral extent of the model.

e. The maximum peak pore pressure values recorded in the field and in the laboratory are found to be about 10% greater than the total stress at the monitoring depth.

f. Peak pore pressures after wick installation approach a minimum value of 1.5psi beyond an Offset Ratio of about 6.

g. The time for full dissipation of wick installation induced pore pressure in compressible soil, which occurs without drainage or settlement, may indicate and relate to a delay in the time for 90% primary consolidation under construction loading.

h. Dissipation of wick installation induced pore pressure occurs after mandrel withdrawal and without measurable change in soil volume, and the reduction in pore water stress is not to be accompanied by stress transfer to the soil matrix.

i. Field research testing can be performed in any type of in situ soil. Where correlation of laboratory and field results is a research requisite, only sites involving insensitive soils can be investigated as remolding is necessary to develop a laboratory model that reasonably reflects in situ soils.

j. A preliminary evaluation of pore pressure and settlement data related to embankment construction at the field test site suggests that the efficiency of wick drain grids is directly related drain spacing.

Recommendations

Five recommendations, as listed below, are presented in an effort to improve procedures currently being applied to the design of wick drain grids to expedite the consolidation of saturated compressible soils subject to construction loading.

a. Develop and evaluate a mathematical model to reflect observed time dependent dissipation of pore pressures induced by wick installation, which occurs without water flow, as the soil drainage and consolidation that relates to the pore pressure reflecting the application of static construction loading cannot occur until the pore pressure increase induced by wick installation is dissipated to a sufficient degree to permit drainage to the wick drain from the soil within its area of influence.

b. Perform field tests in various compressible soils to determine the nature and extent of pressures by circular mandrels as well as mandrels commonly used commercially to install wick drains, in order to develop an empirical basis to improve procedures to estimate the field performance of wick drains during the design phase of a project.

C. Prepare specifications governing methods of installation of wicks and piezometers by means of commercially available soil boring equipment, in order to enable engineers to perform tests in situ to determine the efficiency of wick installations during the design phase of a project.

d. Develop procedures to accurately determine the positions of wicks and piezometers at the monitoring depth needed to profile pore pressures induced by wick installation, and to improve the interpretion of field pore pressure data.

e. Perform investigations to determine the feasibility of using “undisturbed samples” as scalar models to investigate pore pressures induced by wick drain installation.

Design of Wick Drain Systems

The Federal Highway Administration(FHWA) funded the evaluation of field data obtained at the NYSDOT research site related to embankment construction, as well as additional field research which was performed in cooperation with the Illinois Department of Transportation (IDOT). Procedures developed to accurately establish wick to piezometer offsets at the monitoring depth were applied in IDOT research, as was a system for computer controlled field data scanning and acquisition.

Accepted theory and practice applied in the design of wick drain systems is well established(14) and is not further reviewed herein. Based on an evaluation of research data, Landau(23) developed Eq. 1 as an empirical relationship to estimate the amount by which theoretical time for 90% of primary consolidation is to be increased to accurately reflect the field performance of wick drain systems used to expedite settlement under construction loading.

$$t_c = F(n_g)(p_i/s_t)(t_d) \qquad \text{Eq. 1}$$

where: t_c = Time correction
F = Time Correction Factor for site conditions
n_g = Number of wicks in a grid unit (3 or 4)
p_i = Average pore pressure induced in a grid unit
s_t = Total stress at the monitoring depth
t_d = Time for full dissipation of pore pressure induced by wick installation prior to loading

Eq. 1 is expected to be applicable to the design of vertical drain grids of all types as the time increment relates only to the extent to which pore pressure is induced and the time for full dissipation after installation. Eq. 1 will apply to the design of Sandwick installations used in Europe, which involve mandrel driven sand-filled prefabricated geotextile cylinders up to 2.5" in diameter. It is also expected that Eq. 1 will also apply to the design of sand drain grids, should cost-effective equipment become available to install drains 2" in diameter, the effective size of wick drains.

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NYSDOT Geotechnical Bureau personnel involved in implementing the field research, included S. Lamb, R. Schnore, R. Tedesco, J. Iori, D. Suits, Z. Kyfor, T. Carlo, and others. J. Teffenhart supervised NYSDOT Machine Shop personnel in the fabrication and assembly of the steel frame needed to form and house the clay model used in laboratory research at Rutgers University.

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