Experience with Wick Drains in Highway Construction over Soft Clay—Storz Expressway, Omaha, Nebraska

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Wick drains were installed along portions of the 2-mi-long highway embankment crossing up to 50 ft of soft highly plastic clay deposited in a cutoff oxbow of the Missouri River in Omaha, Nebraska. About 1,650,000 lineal feet of 4-in.-wide band-type wick drains were installed in a triangular pattern at spacings ranging from 3.25 to 5.5 ft to facilitate strength gain of the foundation clays during stage construction and to precompress the clays under a surcharge before paving. The wick drains have allowed the excess pore water pressures generated by fill placement to dissipate. Apparent horizontal coefficients of consolidation calculated from pore pressure and settlement observations range from about one-half to several times the values estimated for design. Measurements during three consolidation intervals to date have shown that the wick drains continue to function without significant changes in the apparent horizontal coefficient of consolidation after vertical strains greater than 15 percent and total settlements greater than 5 ft. Instrumentation placed between the wick drains has shown that the apparent horizontal coefficient of consolidation is significantly smaller where the wick drain spacing is 3.25 ft than in similar soil layers where the spacing is 5.5 ft.

The Arthur C. Storz Expressway will be a 1.9-mi-long four-lane divided highway in Omaha, Nebraska. The alignment begins on a loess-mantled terrace overlooking the Missouri River and extends eastward over the flood plain. Thick deposits of soft high-plasticity clay underlie about 60 percent of the alignment. Fill heights of 12 to 30 ft were necessary to construct the permanent embankment and surcharges.

Due to the poor subsurface conditions identified along the alignment, a special foundation stabilization program was developed to satisfy stability requirements and postconstruction settlement criteria. The recommended stabilization program included use of vertical wick drains, stabilizing berms, surcharge fills, and staged embankment construction. Various instruments were installed to provide data with which to evaluate the embankment and foundation performance.

This paper summarizes the design and installation of the wick drains and the observed wick drain performance over a 3-yr period during staged construction.

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SITE CONDITIONS

The presence of thick, soft, high-plasticity clays and the requirement for significant embankment thicknesses resulted in critical stability conditions with significant settlements in two segments of the roadway alignment called the Bluff area and Florence Lake. The centerline embankment geometry and the soil conditions in these areas are summarized in Figures 1 and 2.

The vertical alignment design at the Bluff area required a large cut through the loess mantled terrace and placement of up to 30 ft of embankment over the recent flood plain soils. The subsurface profile at the juncture of the terrace and flood plain deposits consisted of a complex system of low- and high-plasticity clays, silts, and sands resulting from intermittent erosion of the loess terrace and periodic flooding of the Missouri River. This transitional zone ends about 200 ft from the toe of the bluff, and the flood plain deposits become primarily high-plasticity clays overlying a thin sand layer and limestone bedrock. This profile continues for about 1,300 ft with decreasing design embankment height from west to east.

Summarized in Figure 3 are the index properties and stress history within the alluvial soils near Station 202 near the juncture of the alluvial soils and the loess mantled terrace. These soils are highly layered and predominantly low plastic. The initial apparent stress history profile is shown to be complex, being strongly affected by the artesian water conditions at the rock surface and desiccation of surface soil layers. The grading program forced much of the profile into virgin consolidation.

The terrace sands that underlie the loess deposits at the Bluff extend into the flood plain beneath the upper alluvial soils. They form a confined aquifer with preconstruction piezometric water levels extending up to 11 ft above the floodplain surface. The piezometric elevation in the terrace sands appeared to decrease with increasing distance from the Bluff, greatly affecting the stress history and strength of the foundation soils.

Settlement and stability were also critical design issues in a clay-filled oxbow of the Missouri River referred to locally as Florence Lake. Figure 2 shows the centerline embankment geometry and subsurface profile along Florence Lake. Thick deposits of soft high-plasticity clay overlie thick alluvial sands beneath this 3,500-ft segment of the roadway. The maximum clay thickness approaches 50 ft. The index properties and stress history conditions in the Florence Lake oxbow near Station 265

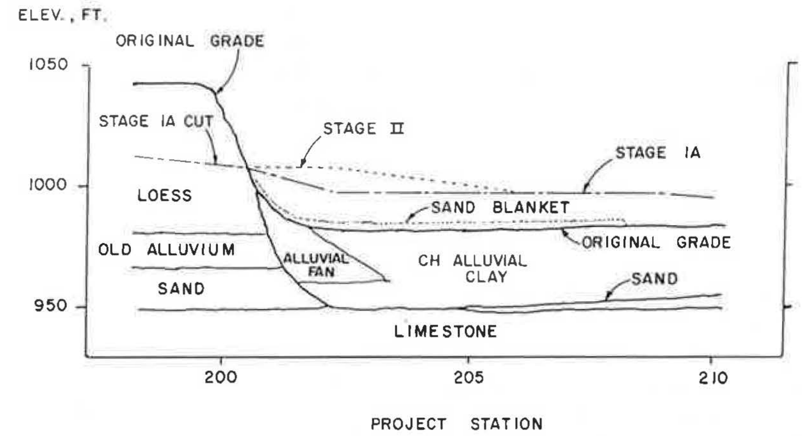


FIGURE 1 Simplified geologic section at Bluff area.

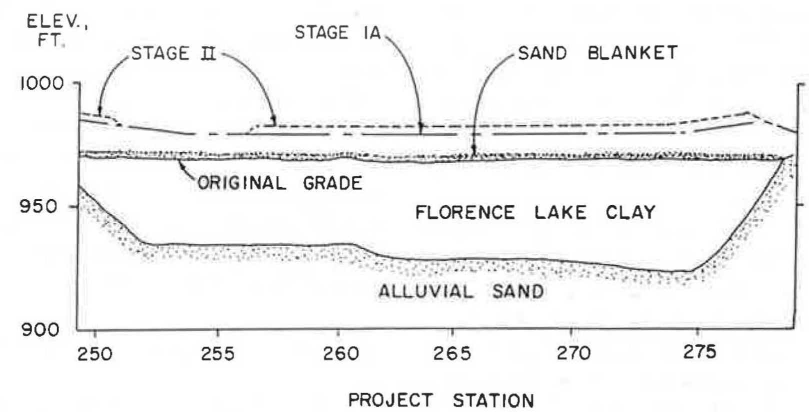


FIGURE 2 Simplified geologic section at Florence Lake.

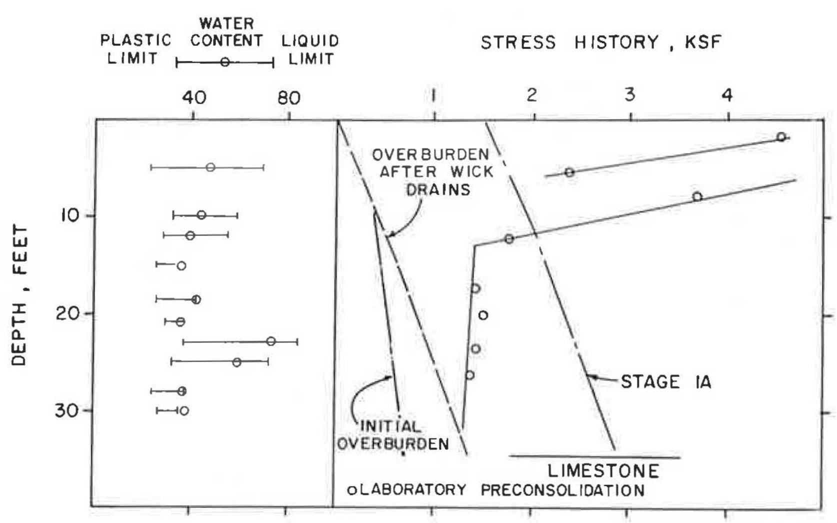


FIGURE 3 Soil conditions at Bluff area, Station 202.

are summarized in Figure 4. The upper 10± feet shows improved strength and precompression from desiccation. The lower clays appear to be nearly normally consolidated. Preconstruction piezometric water levels in the clays and underlying alluvial sands typically varied from about 0 to 4 ft below the ground surface.

EMBANKMENT DESIGN

The embankment design included a stabilization program for the Bluff and Florence Lake areas. The program made use of vertical wick drains, stabilizing berms, preloading with temporary surcharge fills, and staged embankment construction (*1*). The wick drains were to be installed under a pregrading contract beginning in December 1983, and ending in May 1984. The first stage of embankment construction (Stage IA) was scheduled to begin in the spring of 1984 and scheduled for completion in the fall of 1984. Where staged construction was required, the schedule provided for start and completion of the final stage of embankment construction (Stage II) in the spring and summer of 1985. Fine grading and the start of paving were scheduled to begin in the spring of 1987. This schedule allowed a consolidation period of 880 days for single-stage construction. For two-stage construction, consolidation periods of 300 and 550 days were provided for Stage IA and Stage II, respectively. The actual periods required to complete embankment construction were extended and Stage IA was actually completed over a 2-yr time period.

Prefabricated wick drains were selected instead of jetted nondisplacement sand drains based on economy and to accommodate the winter construction schedule. Design of the drain spacing, which varied from 3.25 to 10 ft, used an equivalent drain diameter of 0.22 ft (based on the diameter of a circle with the same perimeter as the wick drain) and a design horizontal coefficient of consolidation (C_h) of 0.05 ft^2 per day (Bluff area) and 0.025 ft^2 per day (Florence Lake) to achieve 90 percent consolidation within the construction schedule. These design C_h values were selected from the results of one-dimensional consolidation tests, an assumed ratio of horizontal to vertical coefficient of permeability of 2, and an assumed 50 percent reduction of C_h as a result of soil disturbance during drain installation. Drain spacing beneath temporary stability berms was based on a 50 percent degree of consolidation between stages.

INSTRUMENTATION

Instrumentation was installed to monitor stability and settlement during fill placement and subsequent consolidation intervals to provide a comparison of predicted and actual behavior and to provide a basis for adjustments in the design, if needed (*2*). Primary instruments to monitor consolidation of the foundation clays included Sondexes that measure relative settlements with depth and pneumatic piezometers at several depths to monitor excess pore water pressure. Inclinometers were used to measure lateral displacements within the foundation clays, both to help assess overall stability and to adjust centerline settlements for the effects of lateral deformation in conjunction with finite element analyses (*3–4*). Typical sections across the embankment and instrument locations are shown in Figures 5 and 6.

Fourteen Sondexes and seventy-three pneumatic piezometers were installed at selected stations along the alignment. These instruments were installed at the center of the triangular spacings before wick drain installation to allow observation of soil behavior during installation of the drains. Remarkably, only two Sondex instruments were damaged by the wick drain mandrel and all piezometers survived the drain installation.

SPECIFICATIONS AND CONSTRUCTION

The wick drains were installed under contract with the Nebraska Department of Roads. The wick drain contract included clearing and grubbing, placement of a 2- to 3-ft-thick

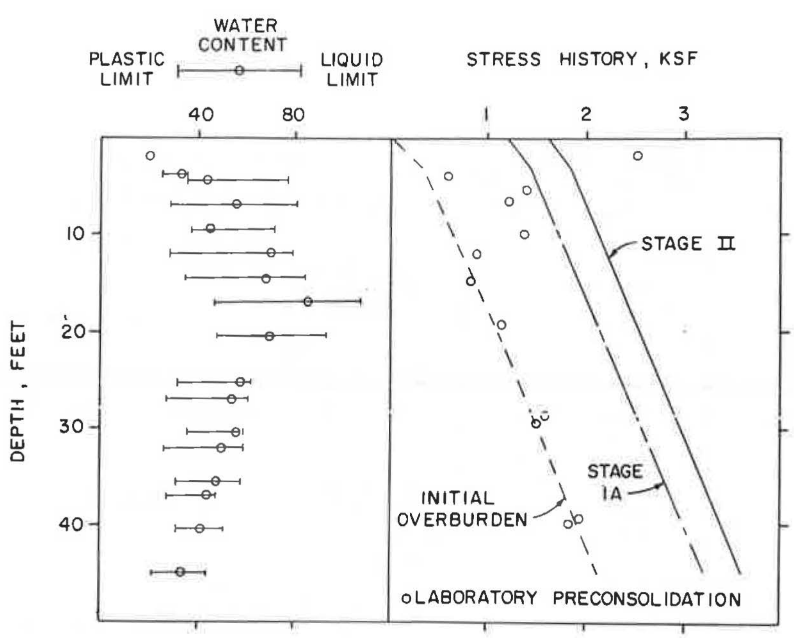


FIGURE 4 Soil conditions at Florence Lake, Station 265.

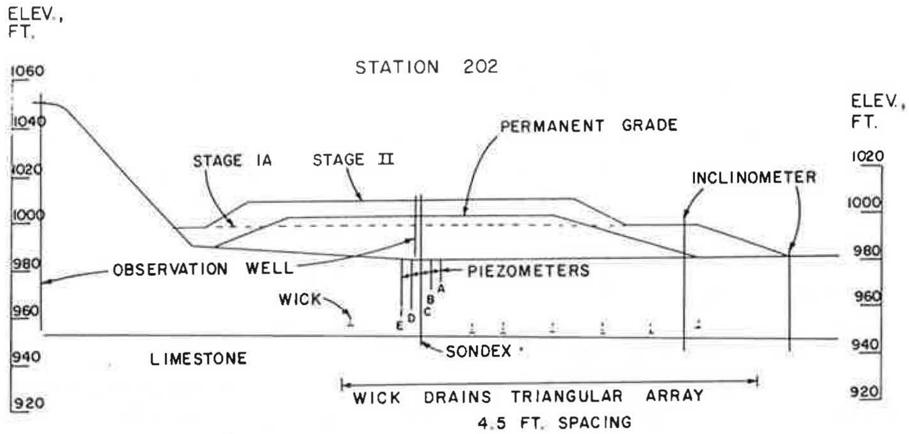


FIGURE 5 Typical embankment section and instrument locations at Bluff area, Station 202.

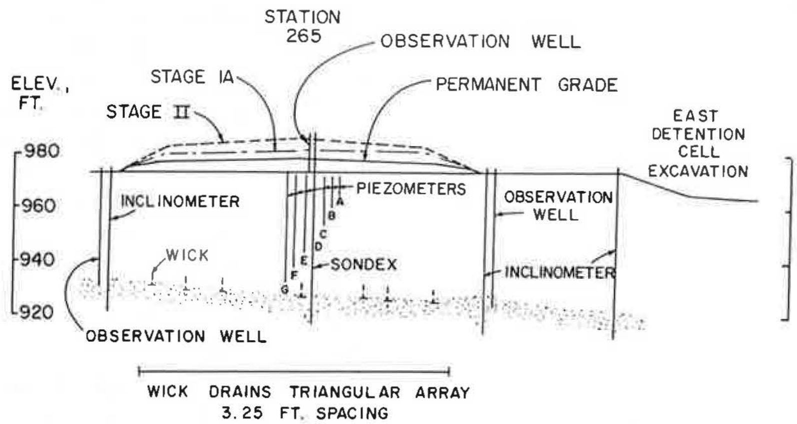


FIGURE 6 Typical embankment section and instrument locations at Florence Lake, Station 265.

sand blanket, installation of a subdrain collection system in the sand blanket, temporary drainage culverts, and wick drains.

Contract documents specified approved wick drain manufacturers. Wick drains were to be the type formed by a band-shaped plastic core which permits continuous vertical drainage wrapped in a separate filter fabric. Specifications called for drains to be installed using a hollow mandrel, with an anchor rod or plate to fix the base of the drain. The mandrel cross sectional area was limited to 10 sq in. to reduce disturbance of the clay. The contractor was required to demonstrate his equipment, methods, and materials by installing 10 trial drains at each of three to five locations designated by the engineer.

Although prequalification of potential contractors was considered during preparation of the wick drain contract, the final specifications did not require experienced specialty contractors. The local contractor that successfully completed the contract had no previous wick drain experience.

Wick drains were installed in a triangular spacing with a 3-in. position tolerance specified. The length of wick drains was documented during installation by observing the depth of penetration of the wick drain mandrel. Payment for the wick drains was made at a contract unit price per lineal foot of installed drain measured from the top elevation of the sand blanket to the tip elevation of the wick drain. Bid quantities for the wick drain contract included an estimated 1,564,840 lineal ft of wick drain.

Three firms submitted bids for the wick drain contract ranging from \$1.69 million to \$1.77 million. Unit prices for installation of wick drains ranged from \$0.33 to \$0.52 per lineal ft and formed about half of the total contract cost. Unit prices for the sand blanket and subdrain system ranged from \$13.37 to \$14.50/cu yd. About 850,000 cu yd of foundation soil were treated with the wick drains resulting in a unit construction cost of about \$2.00/cu yd of treated soil. The costs included mobilization, clearing and grubbing, sand blanket, underdrains, and wick drains. Klaasmeyer Brothers Construction Company of Omaha, Nebraska, completed this work from December 1983 to March 1984.

Initial construction included clearing and grubbing followed by placement of a 2- to 3-ft-thick sand blanket. The sand blanket provided a working surface for installation of the drains and embankment fill placement and provided drainage for water exiting the wick drains.

The contractor fabricated a cable-driven mandrel and leads supported by a crane as shown in Figure 7. Schedule requirements required a second unit for a 2-mo period. About, 40,800 Amerdrain™ Type 401 wick drains were installed with an average length of 40.5 ft. The contractor averaged 370 drains

(15,000 lineal feet) per rig per day through the project during wintertime installation of 1.65 million feet. Maximum installation rates approached 25,000 lineal ft per rig per day. Weather conditions were not a significant factor during drain installation except that work halted when daytime ambient air temperatures fell below 0°F. A backhoe with a pneumatic hammer (pavement breaker) was used periodically to break through frost in the sand blanket before drain installation. Inspection personnel for the wick drain contract included a project engineer and one technician for each rig. The inspector documented the position and length of the wick drains and rejected those not anchored at the base of the clay. Experience showed that a 6-in.-long 3/8-in.-diameter reinforcing rod successfully anchored the drains after about 0.5 ft of penetration into the alluvial sands.

FIGURE 7 Wick drain installation equipment.

OBSERVATIONS OF WICK DRAIN PERFORMANCE

The records of settlement and piezometric elevation with respect to time from the instrumentation provided the basis for evaluation of the effectiveness of the wick drains in accelerating the rate of consolidation of the foundation clays.

Bluff Area

The instrumentation observations at instrument cluster IC202 (Figure 5) located in the Bluff area illustrate the effectiveness of wick drains installed at a 4.5-ft triangular spacing in highly layered soils. The soils in the transition between the loess terrace and the flood plain consist of low- and high-plasticity silty clays interbedded with numerous horizontal sand and silt layers underlain by alluvial sands that transmit artesian water conditions. Figure 8 is a plot of the piezometric elevation and fill height at Instrument Cluster IC202 with respect to time. Very small excess pore water pressures (measured piezometric elevation minus reference piezometric elevation) developed in the foundation clays during filling. The data suggest that the numerous sand and silt layers were effectively dewatered by the wick drains, which greatly improved the vertical drainage conditions in addition to the horizontal flow. Figure 8 also shows a 5± ft drop in the piezometric elevation in the terrace sands following wick drain installation. Visual observation of the subdrains and sand blanket has shown continuing water flow over the past 4 yr. The gradual increase in the piezometric elevation in the terrace sand with time suggests that the drains are progressively becoming less effective in dewatering the higher piezometric elevation. The lower piezometers in the clay do not show a similar increase suggesting that the drains continue to function. The gradual decrease in the piezometric elevation in the sand blanket appears to be due to gradual settlement of the outlets of the subdrain system.

The relationship between embankment loading and settlement at Instrument Cluster IC202 shown in Figure 9 indicates that most of the settlement occurred during loading, which is consistent with the piezometer data. About 2 ft of settlement has occurred under about 28 ft of fill. Further from the Bluff, the sand and silt layers end, and the instruments show slower consolidation consistent with radial drainage in thick clay. These observations are not discussed.

Florence Lake

The observations at Instrument Cluster IC265 (Figure 6) located near the center of Florence Lake provide a representative record of the consolidation behavior of the thick, soft, high-plasticity oxbow clays with wick drains arranged in a triangular pattern and spaced at 3.25 ft. Summarized in Figures 10 and 11 are the observations of piezometric elevation and settlement with respect to time. Before Stage II, a settlement of about 4.2 ft occurred in response to an effective fill thickness (actual thickness minus one-half observed settlement) of 11.5 ft. Measurements of settlement with depth in Figure 12 show maximum strains greater than 15 percent, with an average strain of about 10 percent.

The piezometer data show development of large excess pore water pressures during each of three filling periods (Figure 10), followed by slow rates of dissipation, as would be expected for loads applied to a thick deposit of normally consolidated clay.

Installation of the wick drains in the Florence Lake deposits caused significant excess pore water development as illustrated in Figure 10 by the increased piezometric water elevations recorded at Station 265.

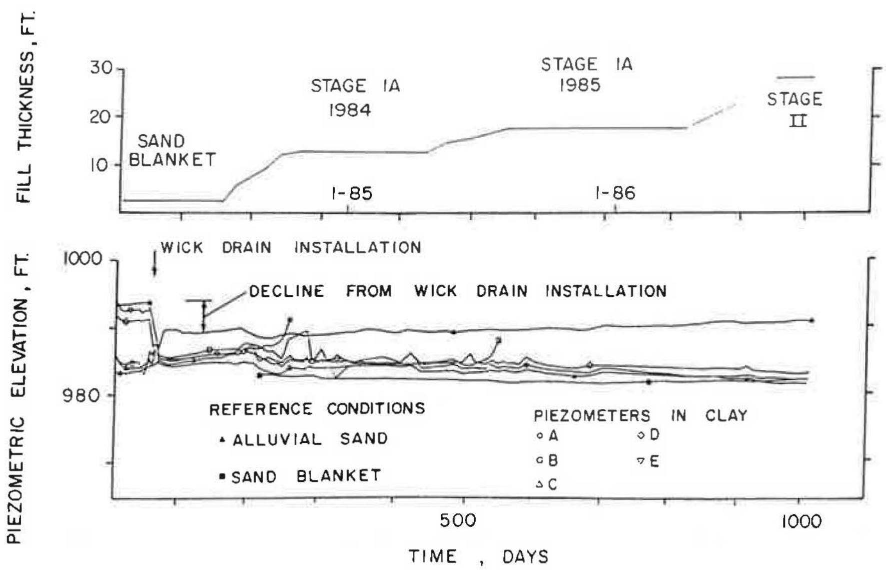


FIGURE 8 Fill thickness and piezometric elevation versus time at Bluff area, Station 202.

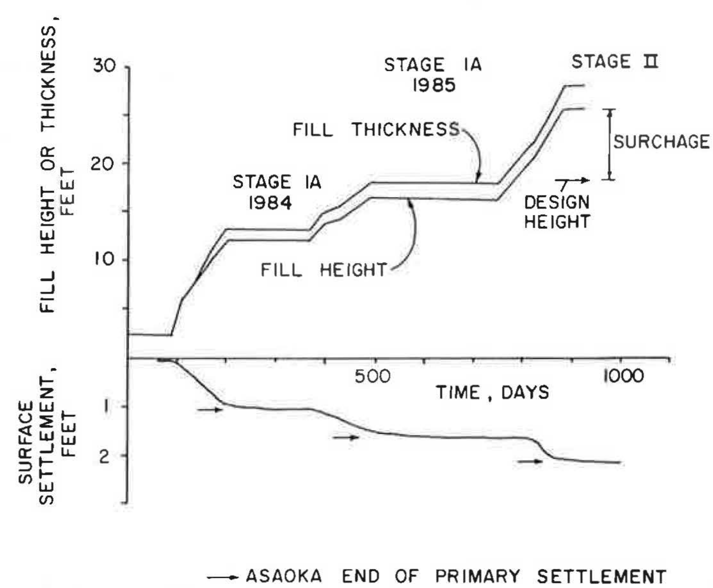


FIGURE 9 Fill thickness and surface settlement versus time at Bluff area, Station 202.

Figure 13 is a plot of the measured increased heads versus depth at five Florence Lake locations with wick drain spacings of 3.25, 5.25, and 5.5 ft. The rather large scatter in the data probably results in part from variations in the actual (versus intended) horizontal distance between the piezometers and the wick drains. The data indicate generally larger heads (4 ± 2 ft) within the normally consolidated clay below 20 ft than at shallower depths (2 ± 1 ft). Somewhat higher values were noted at the three locations with the closest drain spacing.

The rates of pore water pressure dissipation and settlement measured during the consolidation periods after each of the three loadings were analyzed to back calculate (C_h) for the foundation clays. Analyses of the piezometer data used the method developed by Orleach (*5*), as illustrated in Figure 14, which is a plot of the excess piezometric head on a log scale versus natural time. The data should form a straight line for a constant C_h, negligible effects of vertical drainage, and constant load. The slope of this line should give a unique C_h independent of the plan location of the piezometer tip relative to the vertical drains.

Analysis of the settlement data used the Asaoka (*6*) method illustrated in Figure 15. This technique predicts the total settlement at the end of primary consolidation. C_h can be calculated from the slope of the linear portions of the plotted data, again assuming a constant C_h, negligible vertical drainage, and constant load.

Figure 16 is a plot of values of C_h obtained from piezometer and observation well readings during the 1985 consolidation period at five Florence Lake locations. For wick drains spaced at 3.25 ft, most of the data fall within a fairly narrow range with a mean value about one-half of the $C_h = 0.025$ ft^2 per day value selected for design. In contrast, data from areas with

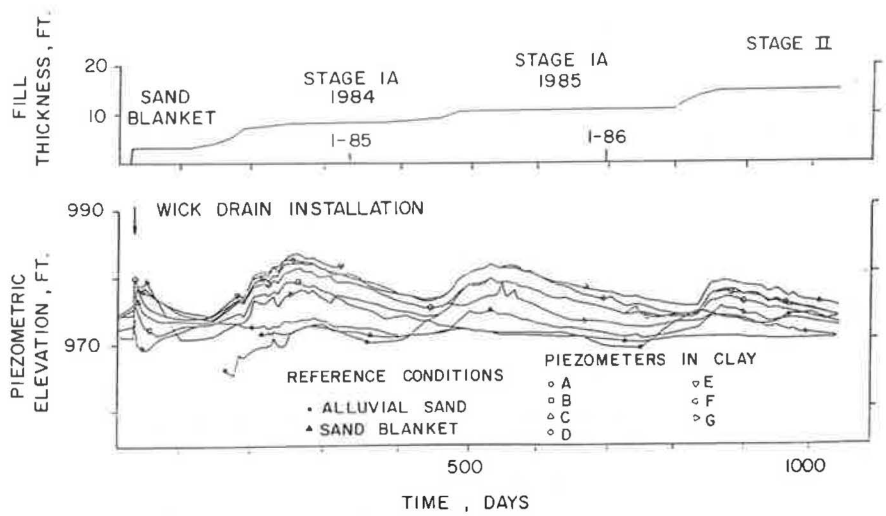


FIGURE 10 Fill thickness and piezometric elevation versus time at Florence Lake, Station 265.

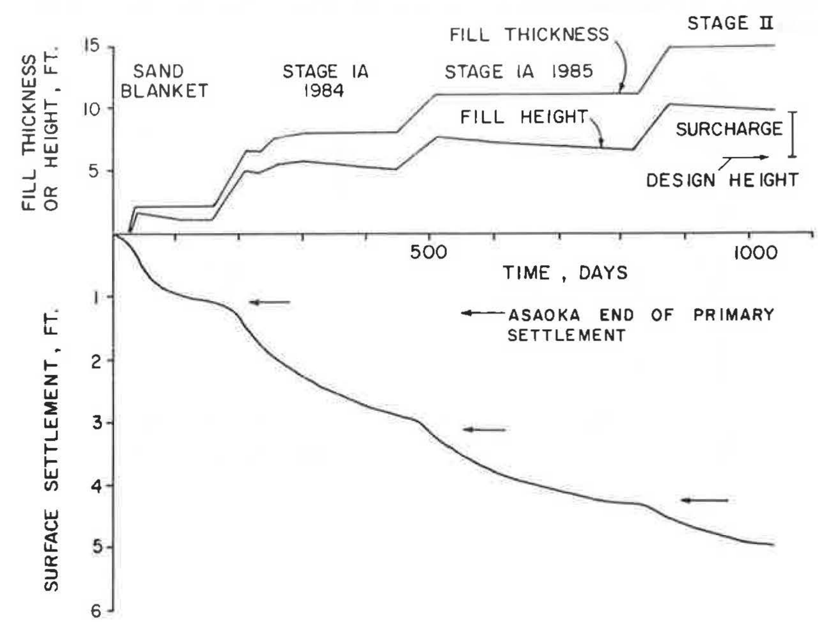


FIGURE 11 Fill thickness and surface settlement versus time at Florence Lake, Station 265.

larger drain spacings yield C_h values scattered about the design C_h except near the bottom of the clays. Vertical drainage near the bottom of the clay may have contributed to pore pressure dissipation resulting in misleading values of C_h determined using the Orleach (5) analysis. The significantly lower C_h at the closest spacing is attributed to increased disturbance of the soft clay during wick drain installation.

The above results and the data shown in Figure 13 suggest an overall degree of soil disturbance from wick drain installation that also may have caused a reduction in the initial undrained strength of the Florence Lake soft clays. Larger than predicted lateral deformations recorded by inclinometers during the 1984 Stage IA embankment construction led to a decision to stop fill placement because of foundation stability concerns. Whether the less stable conditions occurred because of disturbance or variations in the design stress history, undrained strength parameters, or a combination thereof remains uncertain.

DISCUSSION OF WICK DRAIN PERFORMANCE

The design C_h values resulted in a 3.25-ft triangular drain spacing to achieve 90 percent consolidation in the available time period for stage construction within most of Florence Lake. The actual C_h values at this spacing, as measured by the instrumentation, were significantly lower than the design values resulting in a longer time interval for primary consolidation than predicted. It was not necessary to change the construction schedule because fill placement also progressed more slowly than planned. The first increment of fill (Stage IA, Figures 2, 6, and 10) was not completed until the fall of 1985 resulting in an unscheduled consolidation interval during the

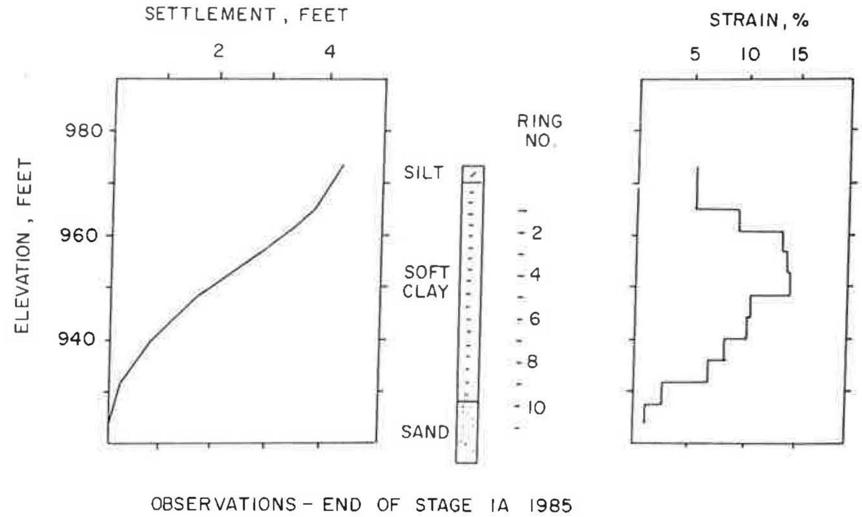


FIGURE 12 Distribution of settlement and strain versus depth at Florence Lake, Station 265.

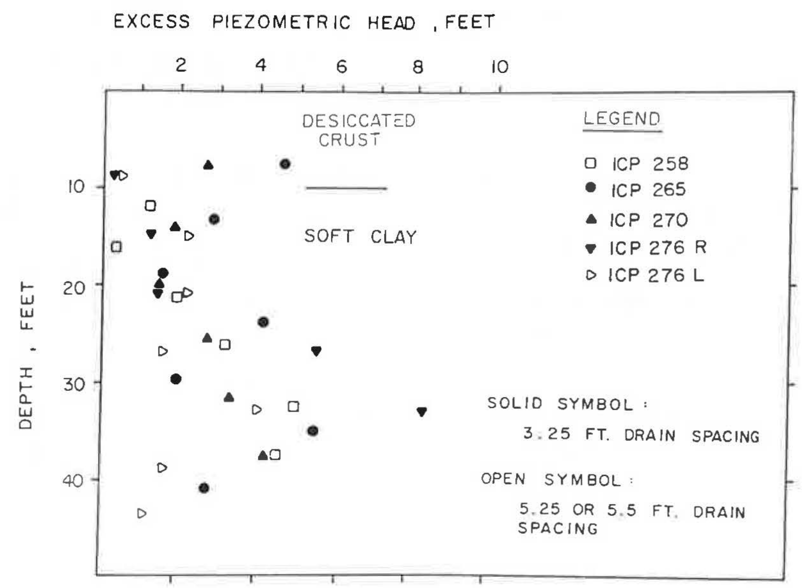


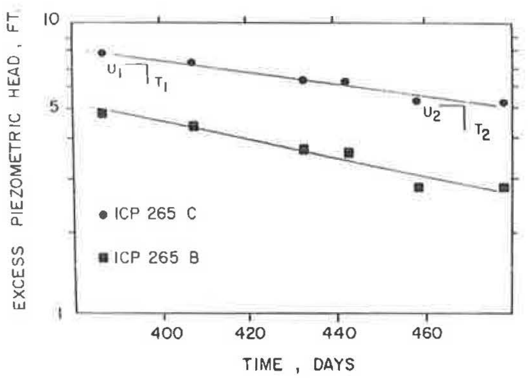
FIGURE 13 Excess piezometric head caused by wick drain installation at Florence Lake.

winter of 1984 to 1985. This prolonged schedule allowed sufficient consolidation to occur before placement of the Stage II fill.

Drain spacing designed to accommodate the C_h values determined from field measurements and the original time schedule would have required decreasing the minimum drain spacing to about 2.7 ft. It is surmised that the smaller drain spacing probably would have caused a further reduction in C_h and possibly more severe stability problems during initial filling due to increased disturbance of the soft clay from wick drain installation.

As previously noted, observation wells were installed in the sand blanket and in the deep alluvial sands beneath the clay to monitor the ambient piezometric elevation necessary for interpretation of the piezometer data. The water level in the deep alluvial sand at Florence Lake varies 4 to 6 ft in an annual cycle related to the navigation season of the Missouri River. In summer, the piezometric elevation rises to near the original ground surface. During this period the drain system discharge increases as water flows from the alluvial sand through the wick drains to the sand blanket and into the subdrain system. The water level in the sand blanket remains relatively constant, matching the invert of the subdrain system. This water flow indicates that the longitudinal transmissivity of the wick drains has not been damaged by the large strains and that the wick drains are in good hydraulic contact with the alluvial sands. In winter, the piezometric elevation in the alluvial sand drops to near or below the subdrain outlet elevation, and the flow from the subdrain system stops.

Based on measurements of the amount and rate of primary settlement following Stage IA filling, the degree of consolidation before paving was estimated and the amount of required surcharge recalculated. Based on these data, the limits and thickness of the Stage II fill were either confirmed or changed.



$$C_h = \frac{(de)^2 \; Fn}{8} \quad \frac{Ln\,(U_1/U_2)}{T_2 - T_1}$$

$$Fn = Ln\,(n) - 0.75$$

$$n = \frac{de}{dw} = \frac{\text{DIAMETER OF DRAIN}}{\text{DIAMETER OF DEWATERED SOIL CYLINDER}}$$

FIGURE 14 Orleach evaluation of C_h, Station 265.

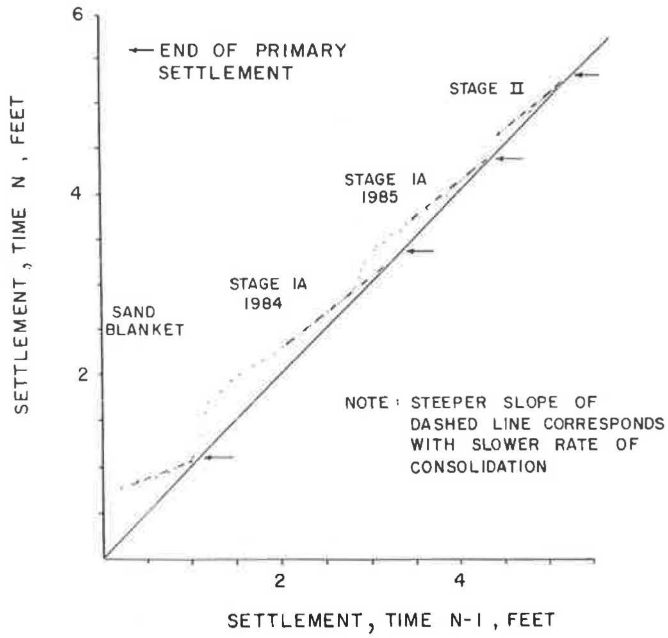


FIGURE 15 Asaoka projection of primary settlement, Station 265.

CONCLUSIONS

Analysis of the field settlement and piezometer data shows that the wick drains significantly reduced the time necessary for primary consolidation of the foundation clays along the Storz Expressway alignment. The wick drains continued to function over a 3-year time period with total settlements of over 4 ft and strains exceeding 15 percent. Significant changes in C_h during consolidation were not noted.

The field observations confirm that installation of the wick drains disturbed the soft Florence Lake clays. Where wicks were installed at a 3.25-ft triangular spacing, the effective C_h values were about 50 percent lower than used for design and about 50 percent lower than where drains were installed at 5.25- and 5.5-ft spacings. Uncertainties in the effects of disturbance from drain installation greatly complicate the selection of drain spacings for foundation stabilization projects with soft clays and a fixed construction schedule. Conservative design estimates of C_h appear justified in determining wick drain spacings.

Where the wick drains intercepted horizontal layers of high permeability, such as existed at the Bluff area, the effective drainage conditions were greatly improved, leading to field rates of consolidation much faster than predicted.

A comprehensive instrumentation system should be an important part of the overall design process for staged

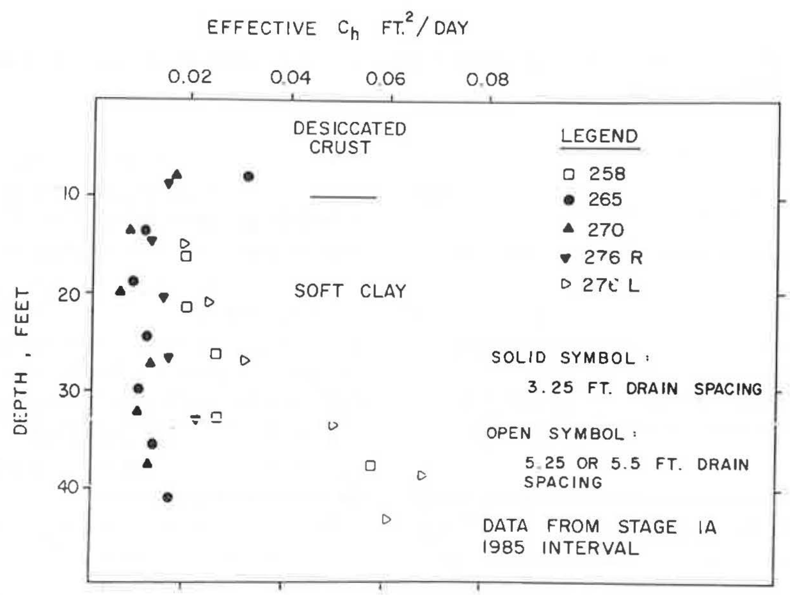


FIGURE 16 Comparison of C_h from different wick drain spacings at Florence Lake based on Orleach analysis of piezometer data.

construction of embankments over soft clays. This project showed that instruments can be successfully installed with drain spacings as small as 3.25 ft without excessive damage during drain installation.

ACKNOWLEDGMENTS

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