Techniques of Backfiguring Consolidation Parameters from Field Data

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Methods of analyzing field consolidation data from areas with and without vertical drains are presented. All methods analyze field data independently of laboratory data. Settlement data from areas having vertical drains can be analyzed by three different techniques to yield values of the apparent coefficient of consolidation and the ultimate settlement for foundation clay. Analysis of piezometer data yields values of apparent coefficient of consolidation by a separate technique. Data from areas without drains can be analyzed for similar parameters. All methods involve the use of Terzaghi's theory of consolidation or Barron's equal strain theory for areas with vertical drains. These theories are appropriate for analysis of most clay deposits. The techniques are illustrated and results from their use on the consolidation of varved clay beneath the approach fills of the Putnam Bridge are presented. These techniques were used in analyzing the data from 49 settlement platforms and two piezometer groups of this project. The results show interesting phenomena that should be explored further with data from other sites.

Piezometers, settlement platforms, and settlement anchors are used to obtain data for the control of fills and preloads over soft clays. The pore pressures are monitored to insure against instability. Future settlements of the fill are a concern when deciding on the time to remove the preload and begin paving. During construction, the devices are carefully monitored and the data faithfully recorded. All documents are usually placed in a file drawer when the project is completed and are too often all but forgotten.

The data from each instrumented fill represent an opportunity to improve our understanding of consolidation behavior and design procedures. This opportunity cannot be realized until the data are properly analyzed. Not every project can be turned into the ultimate research site, but the amount of instrumentation normally used to control construction can, with a little planning, be positioned to effectively yield, upon analysis, important information on the consolidation and settlement behavior of soft soil.

Presented herein are techniques to analyze the settlement and piezometer data from fills placed over clay. There are several benefits from conducting these analyses. The most obvious is the case of the test fill. In this case the analysis of the test fill allows the most economical final design to be made for the entire fill. In general, even though the analysis of data occurs after the project is complete, the comparison of predicted to actual fill behavior gives the engineer insight into improving the design approach on future projects. Analysis is also a good method of exposing the young engineer to the behavior of local clay deposits under fills.

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Field consolidation data must be analyzed by some theory. The analytical procedures presented here are based on the small strain theory of Terzaghi (*1*). The limitations of this theory are well known, but it provides useful information because, for most soft soils capable of supporting a fill, Terzaghi's theory is a good approximation. For the case of vertical drains, Barron's modification using equal strain consolidation is used (*2*), rather than the direct extension of Terzaghi's theory by free strain.

Although the analysis process may be considered an autopsy (*3*), progress in geotechnical engineering, as in medicine, advances by the judicious use of the autopsy. It is important to approach the data with as little bias as possible. Previous observers have noted the ability of some to use field data to prove just about anything (*3*). To avoid this, the techniques presented here analyze the field data independently of laboratory results. In this approach both the coefficient of consolidation and the ultimate settlement are treated as unknowns when analyzing field data. Using laboratory values for the coefficient of consolidation or predicted values of ultimate settlement in the analysis of the field data biases the results toward the designer's assumptions and leads to questions concerning the validity of results and the conclusions that can be drawn from them. Whatever assumptions were used in design are neutralized in the analysis techniques presented here, and better insight is developed into the entire process of investigating and testing soils and designing and monitoring foundations. These techniques are not a replacement for engineering judgment. There are soil deposits for which it is difficult to determine properties for design from laboratory tests (*4*). Analysis of test fills for these cases yields valuable design information.

The procedures are presented for areas with and without vertical drains. The field coefficient of consolidation can be determined from piezometer data and settlement data, both separately and compared to laboratory results. The total settlement for each platform can be calculated from the field data and compared to predicted values.

PLACING THE INSTRUMENTATION

The analysis can only be as good as the data available to it. One limitation of Terzaghi's theory is that it assumes a homogeneous soil. The instrumentation can often be placed to divide the deposit into reasonably homogeneous units that can be analyzed. A location having soil layers with varying properties might be broken down into reasonably homogeneous units for the analysis by gathering data with settlement anchors as well as platforms. A few extra piezometers might be placed to determine the rate of dissipation in contiguous layers having different properties. Stratified alluvia may be the most challenging deposits because the many layers in the soil profile often yield only global average values for the deposit.

The soil conditions that nature provides cannot all be accounted for in a brief paper. Each site requires a bit of ingenuity on the part of the designer of the instrumentation and some intuition when carrying out the analysis.

SETTLEMENTS IN GENERAL

Techniques will be presented for the condition of only one filling phase. They can, however, be used in successive applications for stage construction. Typical data are shown schematically in Figure 1. Figure 1(top) shows the filling sequence for an approach fill to the Putnam Bridge in Glastonbury, Conn. Figure 1(middle) shows the settlements with time at the same location, and Figure 1(bottom) shows piezometer data from the same area.

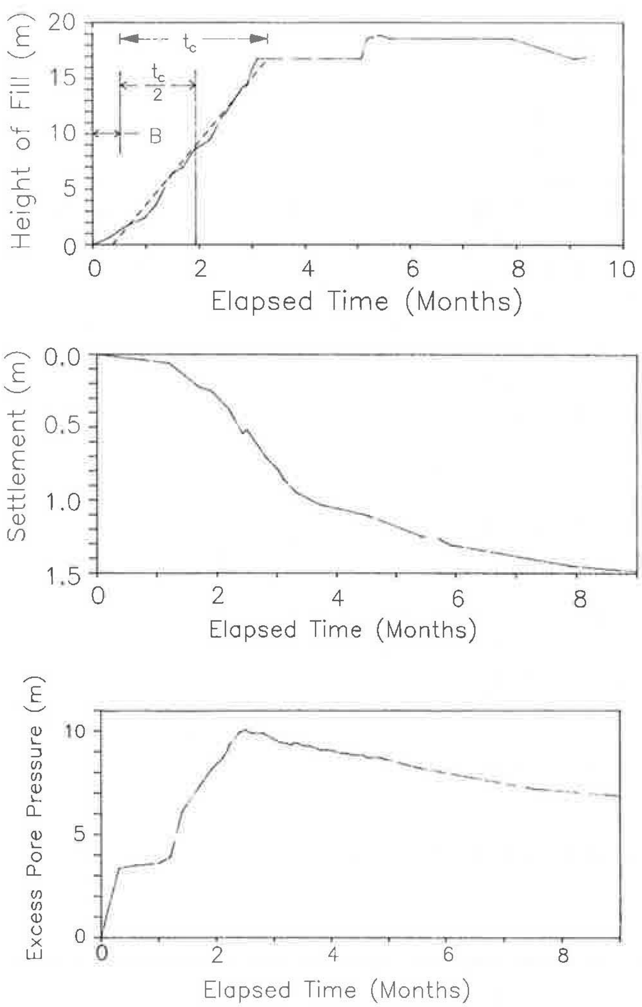

FIGURE 1 Plots of (*top*) fill height versus time, (*middle*) settlement versus time, and (*bottom*) excess pore pressure versus time for settlement platform SP-11, Putnam Bridge.

The settlement observed at any time after filling begins can be described by the equation:

$$\rho = \rho_i + U \rho_c \tag{1}$$

where:

ρ = observed settlement,
ρ_i = immediate settlement,
ρ_c = final consolidation settlement, and
U = average percent consolidation.

Although Equation 1 is valid for any observation of the settlement, the analysis is most easily conducted after the fill reaches final height. When plastic flow of the foundation soils can be neglected, the immediate settlement remains constant under the constant load. In cases where plastic flow is anticipated, slope indicators should be installed along the edges of the fill to measure these strains. More research is required to properly interpret the strains that accompany plastic flow, and the discussion here will be limited to cases where plastic strains can be neglected. When the load, and therefore the immediate settlement, is constant, the changes in the observed settlements are due to increases in the average percent consolidation of the layer.

AREAS WITH VERTICAL DRAINS

Vertical drains are often used to accelerate the consolidation and settlement of clays. The presence of the drains allows the pore pressures to dissipate radially. When analyzing the data, it must be recognized that the pore pressures dissipate vertically as well as radially in areas having vertical drains.

The vertical drainage affects the data from various instruments to different degrees. Piezometer data may be strongly influenced by the dissipation of pore pressures in the vertical direction if they are located near the drainage boundaries where the dissipation of pore pressures is faster than average. To insure that the analysis will yield valid results, one piezometer at each location should be placed where the dissipation of the pore pressures in the vertical direction is slowest (i.e., in the center of the layer for a double drained condition). A schematic diagram showing typical positioning of settlement platforms, and anchors, and piezometers is shown in Figure 2. The piezometer in the center of the layer can be used to determine the coefficient of consolidation in the radial direction. Piezometers such as A and C, placed closer to the upper and lower drainage boundaries, can be used in conjunction with the center piezometer to estimate the vertical coefficient of consolidation.

Settlement platforms yield the necessary data for a deposit that is reasonably homogeneous. Settlement anchors are used to isolate the settlement data from a layer. The data from a settlement platform may show a higher coefficient of consolidation than the data from a piezometer placed in the center of a double drained layer, such as piezometer B in Figure 2. This is because the settlement platform data result from the average consolidation from vertical and radial dissipation combined, while the dissipation at piezometer B is primarily the result of radial flow (*5,6*). The data from piezometers positioned similar to A and C may also show significant effects

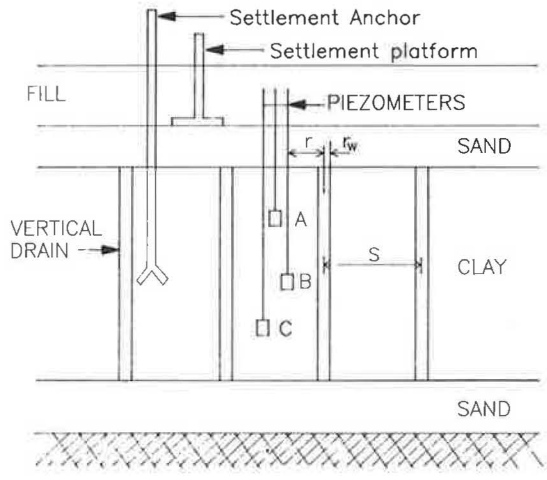

FIGURE 2 Schematic diagram showing typical instrumentation and nomenclature.

of vertical drainage, and caution must be used in the analysis and interpretation of results. An analysis of these drainage conditions has demonstrated that the average consolidation for the layer as represented by settlement with time curve for the top of the clay has approximately the same shape as average consolidation curve for the case of radial flow only and can be analyzed for an apparent coefficient of radial consolidation. The values of the backfigured coefficient of consolidation can be corrected for flow in the vertical direction (*7,8*).

Analyses Based on Settlements

There are several methods of analyzing data from areas containing vertical drains. All use the theory of equal strain consolidation. Substituting for U the expression for average percent consolidation developed by Barron (*2*) yields

$$\rho = \rho_i + \left[1 - e^{(-\lambda t)}\right]\rho_c \tag{2}$$

$$\rho = \rho_t - \rho_c\, e^{(-\lambda t)} \tag{3}$$

$$\lambda = \frac{2\,C_R}{F(n) r_e^2} \tag{4}$$

$$F(n) = \frac{n^2}{n^2 - 1}\ln(n) - \frac{3n^2}{4n^2 - 1} \approx \ln(n) - 0.75 \tag{5}$$

where

ρ_t = ultimate settlement = $\rho_i + \rho_c$,
C_R = apparent coefficient of consolidation in the radial direction,
n = r_e/r_w,
r_e = effective radius of the vertical drain, and
r_w = effective radius of the drain well.

The effective radius is related to the drain spacing, S, as shown in Figure 2, and equals $0.53S$ for a triangular pattern and $0.57S$ for a square pattern.

Rearranging Equation 3 and taking the natural logarithm of both sides,

$$\ln(\rho_t - \rho) = \ln(\rho_c) - \lambda t \tag{6}$$

Equation 6 indicates a straight line relation on a semilog plot between the natural logarithm of a settlement difference and the time. The exponential term having a base e in the basic equations often allows linearization by taking the natural logarithm of both sides of the equation. The reader is cautioned about making plots of data on graph paper having a common logarithm scale. To describe a plot on this type of paper requires the conversion $2.303 \log(x) = \ln(x)$.

If the field observations are continued into the secondary compression region, estimation of the ultimate settlement can be made directly from the data. These cases are rare. For economic reasons, most observations are truncated while the clay layer is undergoing primary compression, and the ultimate settlement must be estimated from the data analysis. An example is the use of Equation 6. Values of ρ_t can be assumed. For each assumed value of ρ_t a straight line can be found to satisfy Equation 6. The goodness of fit for each straight line can be determined through the sum of the errors squared. The ultimate settlement yielding the minimum sum of the errors squared is considered the best fit. It is best to vary the size of the assumed ultimate settlement in a regular fashion. To begin with, a value for the ultimate settlement can be assumed larger than the last observed settlement and a least squares fit of the data to Equation 6 obtained (*9*). A slightly larger value of the ultimate settlement can be assumed and the data fitting and summation of the errors squared repeated. A second sum of the errors squared being smaller than the first indicates a better fit. If the process is repeated a number of times, a pattern as shown in Figure 3 usually develops (*5*). As successively larger values of the ultimate settlement are assumed, the sum of the errors squared first decreases then increases. The value of the ultimate settlement for the lowest value of the sum of the errors squared represents the best fit ρ_t. The best fit ρ_t is used in computing the best fit apparent coefficient of consolidation from the slope and Equation 5. A small computer program can be written to speed up this process.

Taking the first derivative of Equation 3 yields

$$\ln\left(\frac{d\rho}{dt}\right) = \ln(\lambda\rho_c) - \lambda t \tag{7}$$

Equation 7 indicates that if the logarithm of the slope of the settlement curve is plotted against time a straight line will

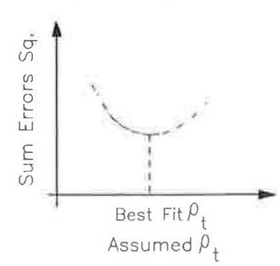

FIGURE 3 Typical plot of data as analyzed by Equation 6 for SP-11, Putnam Bridge.

result. The slope of the straight line, λ, is proportional to the coefficient of consolidation. The theory assumes that the coefficient of consolidation is constant. The slope of the settlement vs. time curve can be determined graphically or from a fitted polynomial (*7,10*). When the coefficient of consolidation decreases with increasing effective stress, the resulting plot is concave upward. To analyze data showing this trend requires an expression for the percent average consolidation that accounts for a decreasing coefficient of consolidation with increasing effective stress (*6*). The use of this approach is beyond the scope of this paper.

Each of these techniques has certain disadvantages. The search routine for Equation 6 occasionally does not converge. The graphical procedure may be considered cumbersome by some. Another method of addressing the data is to consider Equation 3 for successive settlements:

$$\rho_{n-1} = \rho_t - \rho_c e^{(-\lambda t_{n-1})} \tag{8}$$

$$\rho_n = \rho_t - \rho_c e^{(-\lambda t_{n-1})} e^{(-\lambda \Delta t)} \tag{9}$$

Subtracting Equation 8 from Equation 9 yields

$$\rho_n = m\rho_{n-1} + B \tag{10}$$

To use Equation 10, plot successive settlements observed at equal time increments as ρ_{n-1} vs ρ_n. Figure 4 shows a plot of the data for settlement platform SP-11 of the Putnam Bridge east approach fill. The plot results in a straight line, the slope m of which is related to the coefficient of consolidation:

$$m = \exp\left[-\frac{2\,C_r \times \Delta t}{r_e^2\,F(n)}\right] \tag{11}$$

The intercept is related to the ultimate settlement through:

$$\rho_t = \frac{B}{(1 - m)} \tag{12}$$

The results, using several of these techniques on the same data, are shown in Table 1. Settlement data from the east approach fill to the Putnam Bridge were analyzed using Equations 6, 7, and 10. As can be seen from Table 1, the three methods yield comparable results.

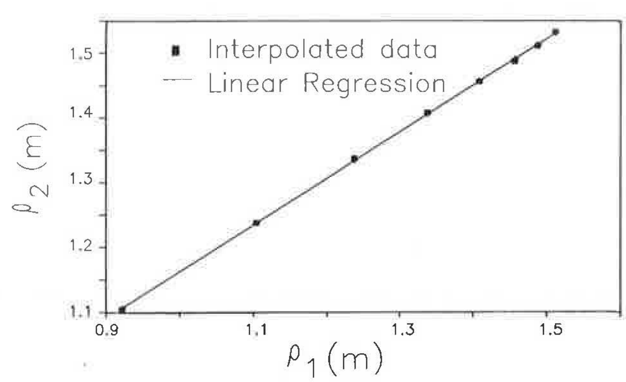

FIGURE 4 Typical plot of data as analyzed by Equation 11 for SP-11, Putnam Bridge.

TABLE 1 COMPARISON OF BACKFIGURED VALUES FROM FIELD DATA AT SP = 11

Coefficient of Consolidation (mm²/sec)	Ultimate Settlement (m)	Method
0.19	1.58	Equation 6
0.18	1.59	Equation 10
0.15	1.62	Equation 7
0.16	—	Equation 16

The data from SP-11 were not observed after equal time increments. The available data was interpolated at the required time intervals after fitting with a smooth curve using a personal computer version of POLYMATH (*10*), which runs on MS-DOS and requires a graphics card. The interpolated values of settlement were then used to complete the analysis. It would be better, when beginning a new project, to observe the settlements after equal time intervals.

Coefficient of Consolidation from Piezometer Readings

Data from piezometers reflecting dissipation in the radial direction, such as piezometer B in Figure 2, can be analyzed according to the equal strain theory of Barron (*2*) as:

$$\frac{u}{u_o} = A\ e^{(-\lambda t)} \tag{13}$$

$$A = \frac{1}{r_e^2 F(n)}\left[r_e^2 \times \ln\left(\frac{r}{r_w}\right) - \frac{r^2 - r_w^2}{2}\right] \tag{14}$$

where

u = excess pore pressure,
u_o = initial excess pore pressure, and
r = radius at which the piezometer is installed (see Figure 2).

Equation 14 indicates that, in cases where the coefficient of consolidation is constant, a plot of $\ln(u)$ against t yields a straight line, the slope of which can be used to compute the coefficient of consolidation thus:

$$\ln(u) = \ln(u_o A) - \lambda t \tag{15}$$

Piezometer data near SP-11 of the Putnam Bridge were analyzed by Equation 15 and also appear in Table 1. As can be seen from Table 1, the value of the coefficient of consolidation backfigured from the piezometer data agrees with the values backfigured from the settlement data. In this example the 28 m vertical thickness of clay, compared to the 3 m spacing of the drains, prevented the vertical dissipation of pore pressure from affecting the data significantly.

A plot of $\ln(u)$ against t for a piezometer may be concave upward for two reasons: (1) a coefficient of consolidation that is decreasing with the increase of effective stress; or (2) a piezometer that is strongly influenced by the vertical dissipation of pore pressures. In the former case, an instantaneous coefficient of consolidation can be obtained from a derivative of Equation 15 thus (*11*):

$$\frac{du}{dt} = -\lambda u \tag{16}$$

where du/dt is the derivative of the pore pressure with time.

The basic piezometer observations with time can be analyzed by several methods to satisfy Equation 16. The derivative can be approximated with the finite difference $\Delta u/\Delta t$ computed for successive observations, but more consistent results are obtained by using all of the data to develop a curve. The slope and values of the pore pressure can be determined graphically from this curve (*12*). Another method is to use POLYMATH to fit a polynomial smooth curve of best fit to the data points (*10*). A derivative of the resulting polynomial can be made by hand or with POLYMATH and the necessary values for Equation 16 computed. At each value of u, λ is computed from Equation 16 and the coefficient of consolidation estimated from Equation 5.

REDUCTION OF THE RESULTS

The apparent coefficient of consolidation and the ultimate settlement are the only two parameters that can be directly estimated from the field data. These results can be reduced into components only if additional assumptions are made. The apparent coefficient of consolidation analyzed from the settlement data can be split into true radial and vertical components with the aid of the approximation (*13*)

$$\frac{\bar{u}_R}{\bar{u}_o} = \frac{\bar{u}_r}{\bar{u}_o} \times \frac{\bar{u}_v}{\bar{u}_o} \tag{17}$$

where

- $\bar{u}_o$ = average initial excess pore pressure,
- $\bar{u}_R$ = average pore pressure indicated by the C_R backfigured from settlement data,
- $\bar{u}_r$ = average pore pressure where the dissipation is only radial, and
- $\bar{u}_v$ = average pore pressure where the dissipation is only vertical.

The values in Equation 18 can be approximated (*13*):

$$\exp\left[-\frac{2\,C_R \times t}{F(n) r_e^2}\right] = \frac{8}{\pi^2} \exp\left[-\frac{2\,C_r \times t}{F(n) r_e^2} - \frac{\pi^2\,C_v \times t}{4\,H^2}\right] \tag{18}$$

and further reduced to:

$$C_R = C_r + \frac{\pi^2}{4}\,\frac{F(n)}{2}\,\frac{r_e^2}{H^2}\,C_v \tag{19}$$

Equation 19 can be solved if the value of C_v or the ratio C_r/C_v is known. The best estimate of C_v would come from a value backfigured from field data collected close to the location at which you wish to apply Equation 19. If a laboratory value of C_v or an approximate ratio of C_r/C_v is used, the values computed with Equation 19 begin to be influenced by speculation rather than fact.

Similarly, the initial settlements can be extracted after a few additional approximations. The theory of consolidation was derived for instantaneous loading, but the sequence of filling in the field requires a number of days or months. Taylor developed a method of adjusting the time of filling to allow the theory to be used to compute settlements for field conditions (*14*). To use this approximation, the load vs. time curve must be able to be approximated by a straight line during the filling stage. An example is shown in Figure 1(a). The dotted line is an approximation of the filling stage. According to Taylor's approximation, the time of consolidation after the fill is complete is computed from the time middle of the filling stage. In this example, average consolidation after about 3.3 months from the beginning of filling are calculated:

$$U = 1 - e^{[-\lambda(t - \frac{t_c}{2} - B)]} \tag{20}$$

where $t_c/2$ equals one-half the estimated construction time and B equals a time adjustment to match the actual beginning of filling.

Equation 20 can now be used with settlement observations at various times after filling is complete to satisfy Equation 1 with the unknowns of ρ_i and ρ_c. Applying Equation 20 to Equation 1 at two well-spaced times allows an estimate of ρ_i and ρ_c, but the additional assumptions required to get to this point must be recognized.

AREA WITHOUT VERTICAL DRAINS

Piezometer Analysis

In areas without vertical drains, sufficient piezometers in each group should be spaced vertically between the drainage boundaries so that the readings can be used to estimate the isochrones within the layer as consolidation progresses. Normally three or more per line are required. These vertical lines of piezometers are usually placed near the centerline of the fill. The dissipation of pore pressures may be controlled predominately by vertical drainage or by a combination of vertical and horizontal drainage. In this technique, one dimensional consolidation in the vertical direction is assumed and the analyzed parameter is called the apparent coefficient of consolidation in the vertical direction, C_{va}. Piezometer groups placed at some distance laterally from the centerline may indicate a slightly different C_{va}, but an analysis to determine horizontal as well as vertical consolidation is beyond the scope of this paper.

In addition to the pore pressure readings, an estimate of the initial excess pore pressure isochrone must be made. This isochrone represents the pore pressures that would be present in the soil were the load applied instantaneously. This isochrone is normally found by calculating, according to some elastic solution, the increased stresses in the vertical direction from the applied load. Other approaches to computing pore pressures are of course possible.

An example of a pore pressure plot is shown in Figure 5. The initial excess pore pressure curve in Figure 5 was assumed equal to the increase in vertical stress. The percent average consolidation is found from Figure 5 by comparing the area under an isochrone to the area under the initial excess pore pressure isochrone with the equation:

$$U = 1 - \frac{A}{A_o} \tag{21}$$

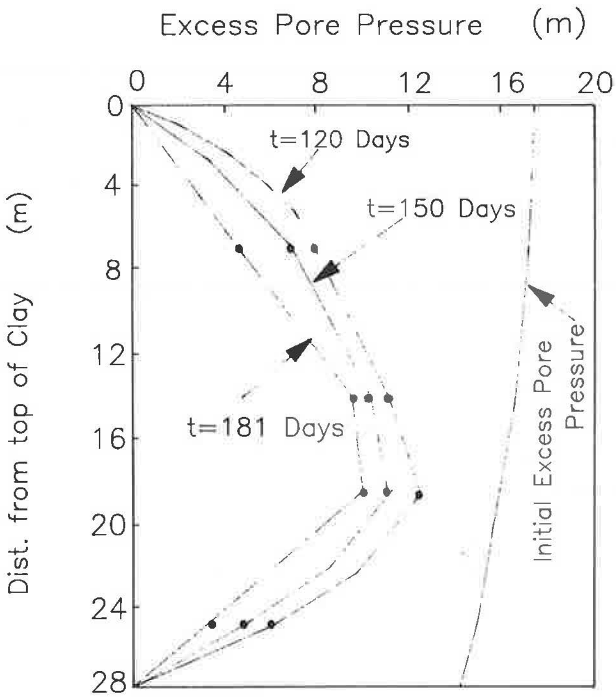

FIGURE 5 Plot of piezometer data for group near SP-66, Putnam Bridge.

where A equals the area under the isochrone at the time of interest and A_o equals the area under the initial pore pressure isochrone.

The area under the isochrones can be measured with a planimeter. Having an estimate of the average percent consolidation at several times allows the apparent coefficient of consolidation to be calculated from Terzaghi's one dimensional theory. For each percent average consolidation, the time factor T has a unique value (*1*). The isochrones occur at different times t. The change between isochrones is therefore represented by

$$\Delta T = \frac{C_{va}\Delta t}{H^2} \tag{22}$$

where H equals the maximum drainage path and Δt equals the change in time. The estimated values of the average percent consolidation can also be used in Equation 1 to determine the settlements.

Analysis Using Settlement Data

A derivation similar to that yielding Equation 11 can be made for areas without vertical drains (*15*). The resulting equation is

$$\rho_n = C\rho_{n-1} + D \tag{23}$$

Equation 23 is applied in the same manner as Equation 10, plotting successive observations of the settlement after equal time increments. The slope c of the resulting straight line can be used to estimate the apparent coefficient of consolidation thus:

$$\ln(C) = -\frac{G\,C_{va}}{H^2} \times \Delta t \tag{24}$$

where G equals a constant. The values of G suggested by Asaoka (*15*) were found by laboratory test to yield values of C_v for one dimensional consolidation that are too low. A derivation similar to Equations 8, 9, and 10 using Terzaghi's theory for average percent consolidation for the one dimensional case of vertical flow yielded a value of $G = 2.47$. This value of G appears appropriate, based on initial experimental results. The ultimate settlement is calculated from:

$$\rho_t = \frac{D}{1 - C} \tag{25}$$

An example of the results of these two analytical approaches is shown in Table 2. Of the two approaches, the one involving Equation 23 requires fewer assumptions and approximations. Settlement platforms are subject to fewer problems than piezometers, and analysis of settlement data often develops results that elicit more confidence.

FILLS AT THE PUTNAM BRIDGE

General Information

The Putnam Bridge crosses the Connecticut River south of Hartford between the towns of Glastonbury and Wethersfield, Conn. To attain the proper navigational clearance over the river, the approach fills on the Glastonbury side required a height of 17 m. The soil profile on which this fill was placed is shown in Figure 6. As can be seen from Figure 6 the site is underlain by about 28 m of varved clay. The bridge was designed and constructed for the Greater Hartford Bridge Authority in 1958. The consultants were Gookind and O'Dea of Hamden, Conn. The analysis reported here resulted from a research project for the Connecticut Department of Transportation at the time that a second crossing of the river was being planned several hundred feet south of the bridge approach described here. The purpose of the research was to reduce the amount of required laboratory testing by analyzing the available field data.

TABLE 2 COMPARISON OF BACKFIGURED VALUES FROM FIELD DATA AT SP = 66

Coefficient of Consolidation (mm²/sec)	Ultimate Settlement (m)	Method
5.8	0.57	Equations 1 and 21
7.0	0.40	Equations 23, 24, and 26

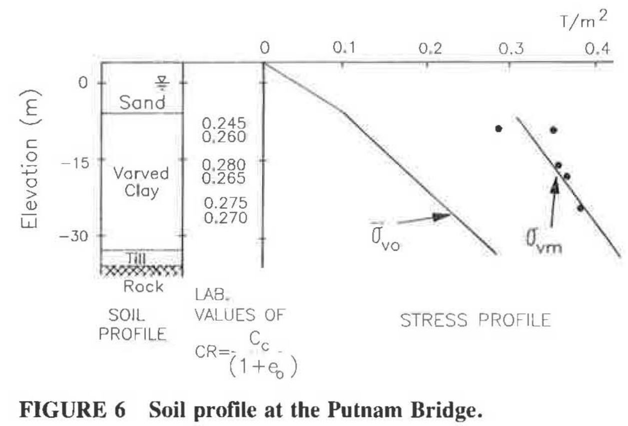

FIGURE 6 Soil profile at the Putnam Bridge.

It was desirable to open the bridge as soon as possible for economic reasons. Berms were used beside the high fill of the east approach to insure stability while allowing the filling to proceed as quickly as possible. Figure 7 shows the locations of the settlement platforms and piezometer groups in the area containing vertical drains. The sand drains were 0.46 m in diameter and spaced at 3.0 m centers in the western end, where the fill was highest. The spacing of the drains was increased to 4.6 m centers as the required fill height decreased toward the east. The sand drains were installed with hollow stem augers (*16*). The settlement platforms were placed on the original ground surface. It was important to monitor the progress of consolidation and settlement to insure that the bridge could open at an early date. However, premature paving of the approach would lead to increased maintenance costs in the future due to excessive post-construction settlements. As a result, careful monitoring of the consolidation process was necessary.

A plan of the portion of fills in which no vertical drains were used is shown in Figure 8. This figure also shows the locations of the settlement platforms and piezometer groups. The piezometers were the Casagrande hydraulic type. The contractor was responsible for the installation. The instruments were monitored by the consultant. It is not known what type of data analysis, if any, was planned at the time of construction.

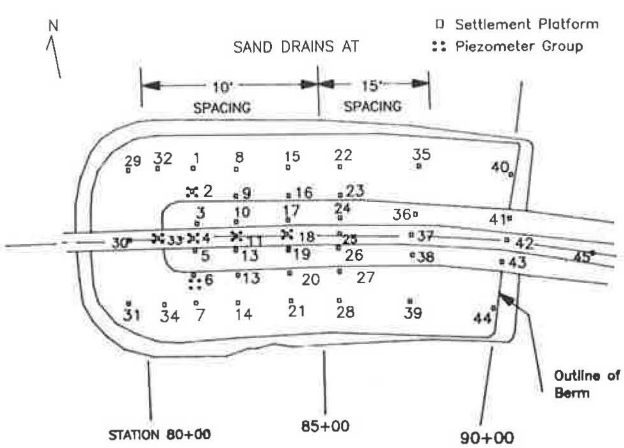

FIGURE 7 Layout of instrumentation at the area with vertical drains at Putnam Bridge (note location of SP-11 piezometer group).

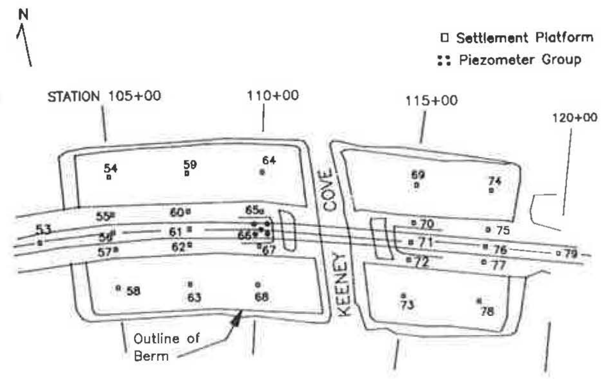

FIGURE 8 Layout of instrumentation at the area without vertical drains at Putnam Bridge (note location of SP-66 and piezometer group).

Varved clay of the Connecticut River Valley in the vicinity of Hartford often shows a laboratory coefficient of consolidation of about 1.1 mm²/s in the overconsolidated range. Larger values often observed in the field have been attributed to the dissipation of pore pressures along the horizontal varves and occasional sand seams (*17*). Horizontal dissipation can account for the values of C_{va} shown in Table 2.

Analysis of Data

The mortality of piezometers was great in the vicinity of the high fills due to the large settlements. Some piezometers showed little dissipation after filling, indicating that they had been pinched off. Only the piezometers showing regular behavior were selected for analysis. Review of the piezometer data found only two sets of piezometers showing the regular dissipation expected in consolidation. Fortunately, one set near settlement platform SP-11 was in the area with vertical drains, and one set near settlement platform SP-66 was in the area having no vertical drains. Settlement platforms are less susceptible to problems. Most of the platforms shown in Figure 7 and Figure 8 survived the construction process and their data could be analyzed.

The appropriate piezometer readings and all settlement platform data readings were analyzed by the techniques described here. Settlement analyses in the sand-drained area were made with the graphical technique and Equation 7, as well as Equation 6 and Equation 11. The three approaches gave comparable results. The analyzed values for the coefficients of consolidation are shown in Figure 9. There was no attempt to correct the backfigured coefficient of consolidation for vertical flow because of the thickness of the clay deposit.

As can be seen from Figure 9, there appears to be a relation between the spacing of drains and the coefficient of consolidation backfigured from the field data. The values are essentially below 10 m²/year for the drains on 3.0 m spacing, regardless of fill height, and 10 to 30 m²/year for the drains at 4.6 m spacing. Similar phenomena have been observed previously (*18*). The differences have been attributed to disturbance that has more effect at the smaller spacing.

The ultimate settlements are plotted against fill height in Figure 10. The data in Figure 10 show that the area having drains with 3.0 m spacing experienced more settlement under

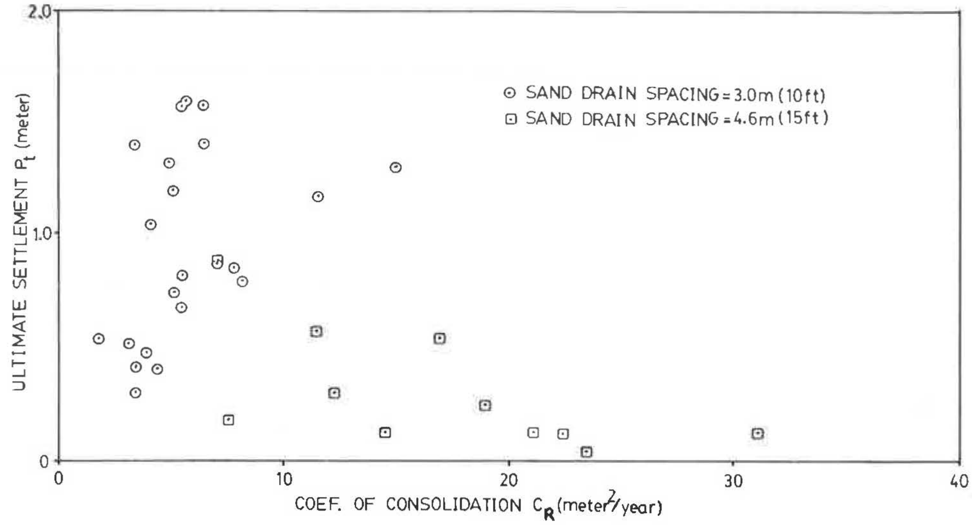

FIGURE 9 Plot of the backfigured coefficient of consolidation versus the ultimate settlement from the settlement platforms in the vertically drained area.

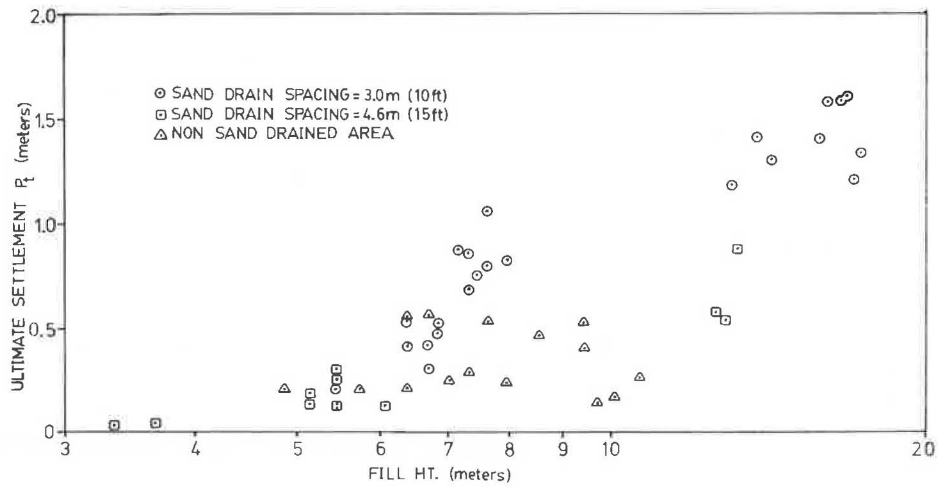

FIGURE 10 Plot of backfigured ultimate settlement versus the fill height over the settlement platforms.

a given fill height than either the area with drains at 4.6 m spacing or the undrained area. This might also be the result of disturbance. The settlement contours are plotted in Figure 11 and Figure 12. As can be seen from these two figures, use of these techniques gave a complete picture of the field behavior. The backfigured settlements are regular with the greatest settlement occurring under the highest part of the fill.

CONCLUSIONS

1. Field consolidation data can be analyzed independently of laboratory data.
2. Small strain theory for areas with and without vertical drains is a valid approximation to the field behavior.
3. Field settlement data can be analyzed for both apparent coefficient of consolidation and ultimate settlement.
4. Piezometer data can be analyzed for the case of constant and decreasing apparent coefficient of consolidation.
5. Vertical drains at 3.0 m spacing at the Putnam Bridge showed a smaller apparent coefficient of consolidation than the drains spaced at 4.6 m.
6. The closer-spaced drains also showed higher settlements than the wider-spaced drains under equal heights of fill.

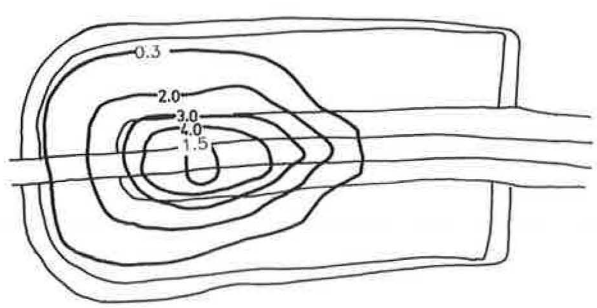

FIGURE 11 Ultimate settlement contours, in meters, for the area with vertical drains.

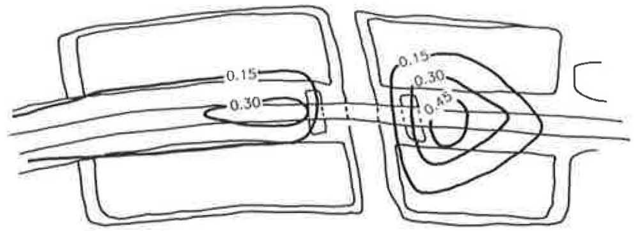

FIGURE 12 Ultimate settlement contours, in meters, for the area without vertical drains.

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