Analyzing Field Data for Initial Settlements

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Introduction

Recent investigations indicate that initial settlements due to elastic shear strains or a combination of elastic and plastic shear strains may contribute significantly to the total settlement of structures founded on clay when the factor of safety is less than about 3 (1,2,3,4). These strains occur throughout the loading sequence causing settlements without volume change in the clay. The term shear-strain settlement seems more appropriate to the field because the load is placed over a period of time. Significant shear-strain settlement can occur in situations previously thought to experience only one-dimensional consolidation settlements (3).

During the construction period both shear-strain and consolidation settlements occur. The proper analysis of field data must distinguish between shear-strain and consolidation settlement. Failure to accomplish this in the past has led to inaccuracies in the evaluation of the coefficients of consolidation and compression from field data.

A method is presented herein that allows direct evaluation of shear-strain settlements from construction records and settlement platform data. This method is applied to field observations made during and following the construction of several bridge-approach embankments on varved clay deposits in the Hartford, Conn. area.

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The results compare favorably with those calculated using data from piezometers installed along with the settlement platforms. This method provides a simple tool by which the practicing engineer can analyze construction settlements using settlement platform data only.

Description of Field Sites and Data

The field data used in this study were obtained from the Soils Division of the Connecticut Department of Transportation. The data included construction records and settlement platform and piezometer observations for two sites. One site, shown in Figure 1, is the highway interchange on the East side of the Charter Oak Bridge in East Hartford, Connecticut. The other site is the East approach to the Bissell Bridge in Glastonbury, Connecticut, which is about three miles south of the Charter Oak Bridge. A plan of the Bissell Bridge approach fill is shown in Figure 2. Both of these sites are located over the varved clay of the Connecticut River Valley.

Only settlement platforms located near a piezometer group having a minimum of three piezometers spaced uniformly with depth throughout the varved clay were selected for analysis. Figure 3 shows the soil profiles at the selected settlement platforms. The varved clay deposits can be considered of constant thickness in the vicinity of each settlement platform.

Typical data used in this analysis are shown in Figures 4 and 5. Figure 4a shows the construction record of filling at settlement platform 13 near the Charter Oak Bridge. Figure 4b shows the observed progress of settlement at the same platform. Piezometer behavior indicated that the hydrostatic excess pore pressures were essentially zero at the top and bottom of the clay. Isochrones were reconstructed from the piezometer data as shown in Figure 5. The data shown in Figure 5 are from piezometers at location 13. The initial excess pore pressure isochrone shown in Figure 5 was estimated from the response of the piezometers to filling. This method of determining the initial excess pore pressure isochrones was used for all of the settlement platforms near the Charter Oak Bridge. The initial pore pressures for the Bissell Bridge locations had to be computed using ICES-SEPOL.

Methods of Analysis

The objectives of this study were not only to analyze the data at hand for initial settlements but also to develop a simple general method for extracting initial settlements from field data. A new method of analysis, called the Square-Root of Adjusted-Time Method, was developed and the results using this technique are compared with the familiar technique using percent consolidation and settlement observations.

1. Description of the Square-Root of Adjusted-Time Method

This method is based on two time-compression characteristics of one-dimensional consolidation. 1. The square root of time is a well known method for evaluating the coefficient of consolidation from laboratory oedometer data (11). The theory indicates that the plot of sample compression against the square root of time yields a straight line from 0 to 60 percent average consolidation. When there is no initial settlement due to compression of gas a straight line through the experimental points up to 60% consolidation extrapolates through the origin. 2. When a clay is loaded at a constant rate in a one-dimensional test, theory indicates that the consolidation settlement at the end of the loading period is approximately equal to the settlement that would have occurred during one-half the same time if the load had been placed instantaneously (12).

These two characteristics can be used to analyze field data for shear-strain settlements by working with the settlement observations after the load is complete. The settlements occurring after the construction are due to consolidation only. To analyze for initial settlements by this method, the observed settlements after the entire load is in place are plotted against the square-root of adjusted-time. Adjusted time is defined as:

$$t' = t + \frac{t_c}{2} \qquad 1$$

where: t' is the adjusted time, t is the time lapsed since the completion of filling and t_c is the equivalent construction time. An example of the equivalent construction time is shown in Figure 4. The area under the load versus time curve during construction is approximated by the area under a straight line ending at the time representing the completion of filling. The horizontal projection of this straight line is t_c. The settlement observation plotted against the square-root of adjusted-time from a straight line is shown in Figure 6. The data in Figure 6 are from settlement platform 13. The extrapolation of the straight line to the vertical axis accounts for the consolidation settlement that has occurred since construction began. The intercept on the vertical axis is the initial settlement due to shear-strains. When there is no initial settlement the data extrapolate through the origin.

The equivalent construction time can be determined in other ways. The straight line which approximates the rate of loading can begin at the start of filling and extend into the time when the load is complete. When using this approximation the plotted settlements are larger but the straight line must be extrapolated further to reach the vertical axis yielding about the same initial settlement. When fills are constructed in stages there is often a time lapse of several months before filling resumes. In these cases the initial settlement for the entire fill can be determined by applying the square-root of adjusted-time method to each stage and adding the results.

2. Theoretical Verification of the Technique

The square-root of adjusted-time method was developed from the one-dimensional theory of consolidation. To verify this approach for cases allowing dissipation of hydrostatic excess pore pressure in more than one direction, plots were made of theoretical values of percent consolidation against the square root of time factor. Eight theoretical treatments of consolidation involving dissipation of hydrostatic pore pressure in more than one direction were plotted against the square root of the time factor. In each case a plot of percent consolidation against the square root of time was found to yield a straight line up to at least 50 percent consolidation. The extrapolated straight line intercepted the vertical axis close to the origin. An error investigation was conducted on each plot by ignoring the first two plotted points and fitting the remaining points with a straight line. The results of this portion of the study are summarized in

Table I. The maximum absolute error was found to be 8.5 percent based on average consolidation for the cases considered. Four of the cases shown in Table I are from Gibson et al (5). The other four are from a model that considers pseudo-two dimensional consolidation as shown in Figure 7. The model was for a strip load 100 ft (30.5 m) wide resting on a clay layer 100 ft (30.5 m) thick and considered drained top and bottom and at horizontal faces 150 ft from the centerline of the load. This model allowed a check of the technique for soils that have permeability in the horizontal direction greater than the vertical. The average percent consolidation for the model was determined by applying the equation: (9)

$$U = 1 - (1 - U_h)(1 - U_v) \qquad 2$$

where: U is the average percent consolidation for the layer, U_h is the percent consolidation due to vertical drainage only.

3. Experimental Verification of the Technique

The validity of the technique was checked by comparing initial settlement results against the results using an analysis involving percent consolidation.

A more familiar method of analyzing field data is the use of piezometer readings to determine the percent consolidation and the settlement platform observations to evaluate the magnitude of settlement. The contributions to the observed settlement can be formulated into the equation: (4)

$$\rho = \rho_i + U \rho_c \qquad 3$$

where: ρ is the observed settlement, ρ_i is the initial settlement

TABLE I

Estimate of Possible Error in Initial Settlements Determined by the Square-Root of Time Plot

Shape of Loaded Area	k_h/k_v	$\frac{h^*}{b}$	Possible Error as Percent Consolidation	Source from which plot was made
Strip	1.0	0.2	5	Gibson et al (5)
Strip	1.0	0.5	8.5	
Strip	1.0	1.0	4	
Circular	1.0	1.0	3	
Strip	5.0	2.0	3	Computer Program
Strip	12.5	2.0	2	
Strip	25.0	2.0	5	
Strip	1.0	2.0	3	

*h = thickness of clay

$$b = \begin{cases} \text{one-half width of loaded area for strip loading} \\ \text{or} \\ \text{radius of loaded area for circular loading} \end{cases}$$

due to shear stress, U is the appropriate percent average consolidation and ρ_c is the consolidation settlement at long times after the fill is in place.

Eq. 1 can be applied to the data after all the fill is in place and initial settlements are complete. Time delay in initial settlements is short in most soils but has been found significant in sensitive clays. When doubt arises as to the shear-strain-time behavior of a load on a clay deposit, Eq. 1 should be applied to the data at long times after the completion of filling. The useful life of most piezometers ends before the secondary compression settlements become significant.

The boundary conditions established by field loads and geometry of the soil strata usually allow drainage in more than one direction. The exact percent consolidation for most field cases is given, therefore, by the ratio of the consolidation settlement at the time of interest to the ultimate consolidation settlement (7). The exact definition of percent average consolidation is difficult to apply to field data because the ultimate consolidation settlement is seldom apparent. Determining the percent consolidation by comparing the hydrostatic excess pore pressures at some time with the initial pore pressures generated by the load is valid for one-dimensional consolidation but results in some error when drainage occurs in more directions. The error in percent consolidation due to this method of determining percent average consolidation was studied by Davis and Poulos (4) who found the error to be small. For the analysis of field data the values of average percent consolidation determined from hydrostatic excess pore pressure isochrones are within acceptable limits.

Both the initial hydrostatic excess pore pressures and those at the time of interest can be plotted to scale and the isochrones for the entire clay layer reconstructed as shown in Figure 5. The approximate percent average consolidation can then be found by comparing the areas under the isochrones in the equation: (6)

$$U = 1 - \frac{A}{A_o} \qquad 4$$

where: A is the area under the isochrone at the time of interest and A_o is the area under the initial hydrostatic excess pore pressure isochrone.

The areas used in Eq. 3 were measured with a planimeter. The average percent consolidation was then used in Eq. 2 with the appropriate observed settlement. At least two determinations of the average percent consolidation are required to solve Eq. 2 since it contains two unknowns: ρ_c and ρ_i. A minimum of three were used in this study and the initial settlement taken as the average of the results.

Results of Field Data Analyses

The results of the analyses of the field data from seven settlement platforms are shown in Table II. The initial settlements as determined by the two methods are given in columns 2 and 3. The maximum difference between results for the varved clay is about 10% which for this data is one inch (2.5 cm).

Analyses of the data from the varved clay indicate that the initial settlements constitute a substantial portion of the total

TABLE II

Summary of Initial Settlement Results

East Hartford Expressway

Settlement Platform Number	Initial Settlements, ρ_i, in feet (cm)		Total Settlement ρ_t in feet (cm)	ρ_i/ρ_t Percent
	Average Percent Consolidation Method	Square-Root of Adjusted-Time Method		
13	0.43 (13.1)	0.39 (11.9)	1.07 (32.5)	36
8	0.49 (14.9)	0.50 (15.2)	2.02 (62.0)	25
4	0.35 (10.6)	0.32 (9.8)	1.43 (43.5)	22
3	0.56 (17.0)	0.63 (19.2)	3.41 (104.0)	18

Bissell Bridge - East Approach

Settlement Platform Number				
A	0.40 (12.2)	0.35 (10.6)	1.15 (35.0)	30
B	0.88 (26.7)	0.88 (26.7)	1.88 (57.2)	47
C	0.22 (6.7)	0.27 (8.2)	0.85 (25.8)	32

settlement experienced by the fills that are between 20 and 40 ft high (6.1 to 12.2 m) the total settlement being the initial settlement plus the ultimate consolidation settlement determined from Eq. 3. The ratios of initial to total settlement for the settlements analyzed are shown in Table II. The ultimate consolidation settlements in the varved clay are approximately equal to the amounts computed using the effective-stress-strain results from laboratory one-dimensional compression tests.

The coefficient of consolidation must remain constant to apply the square-root of adjusted-time method. This condition is not necessary for the average percent consolidation method using piezometer data. The coefficient of consolidation for this varved clay was found to be reasonably constant for each settlement platform investigated but the relation between the level of effective stress and the coefficient of consolidation should be checked from field data for each clay deposit. If the coefficient of consolidation decreases with increasing effective stress, the square-root of adjusted-time will yield initial settlements that are too large.

The analyses techniques were also tried on data previously published for different clays (7)(10). The data in the articles were not as complete as that available on the varved clay. Nevertheless, the results indicated an agreement similar to those reported here.

Initial settlement information can be put to design use in several ways. Knowing the initial settlement and the applied load a theory similar to that proposed by D'Appolonia et al (3) could be used to backfigure the undrained Young's modulus (E_u) which could then be used for future design. An alternate approach is to analyze all available data from a clay deposit for initial settlements and from the results and the loading configurations estimate the amount of initial settlement to be expected on future projects.

Conclusions

1. Initial settlements may comprise a substantial portion of the total settlement experienced by a load on clay.
2. When the coefficient of consolidation remains constant, the Square-Root of Adjusted-Time Method is the simplest technique for extracting initial settlement from field data.
3. When the coefficient of consolidation changes with effective stress, only the average percent consolidation method can be used.

Acknowledgement

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APPENDIX - REFERENCES

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LEGEND FOR DIAGRAMS

Figure 1 Plan of Piezometer Groups and Settlement Platforms Near the Charter Oak Bridge.

Figure 2 Plan of Piezometer Groups and Settlement Platforms in the East Approach to the Bissell Bridge.

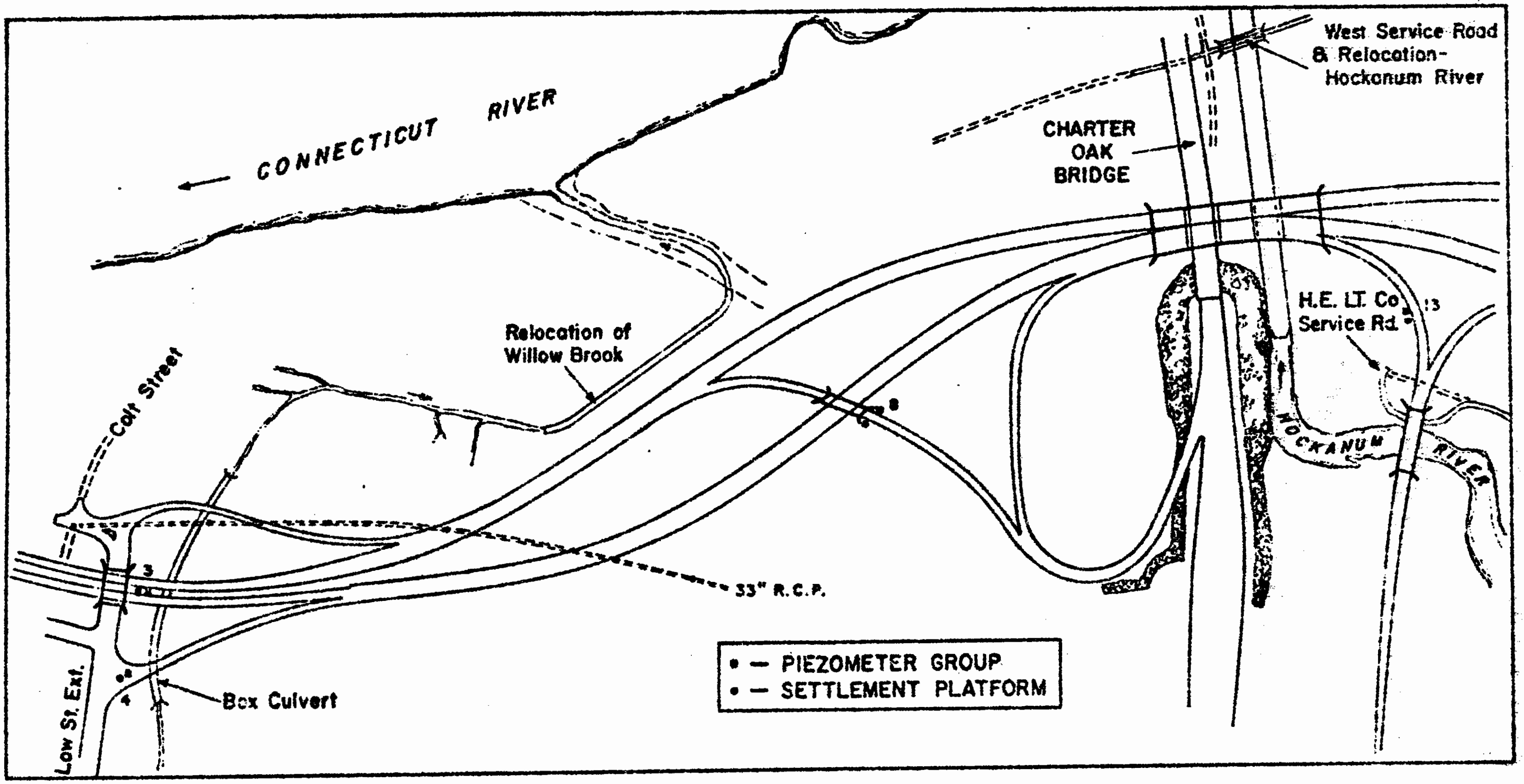
Figure 3 Soil Profiles at the Locations Selected for Analysis.

Figure 4 Construction Records at Settlement Platform 13 Near the Charter Oak Bridge: 4a Filling rate; 4b Observed Settlement.

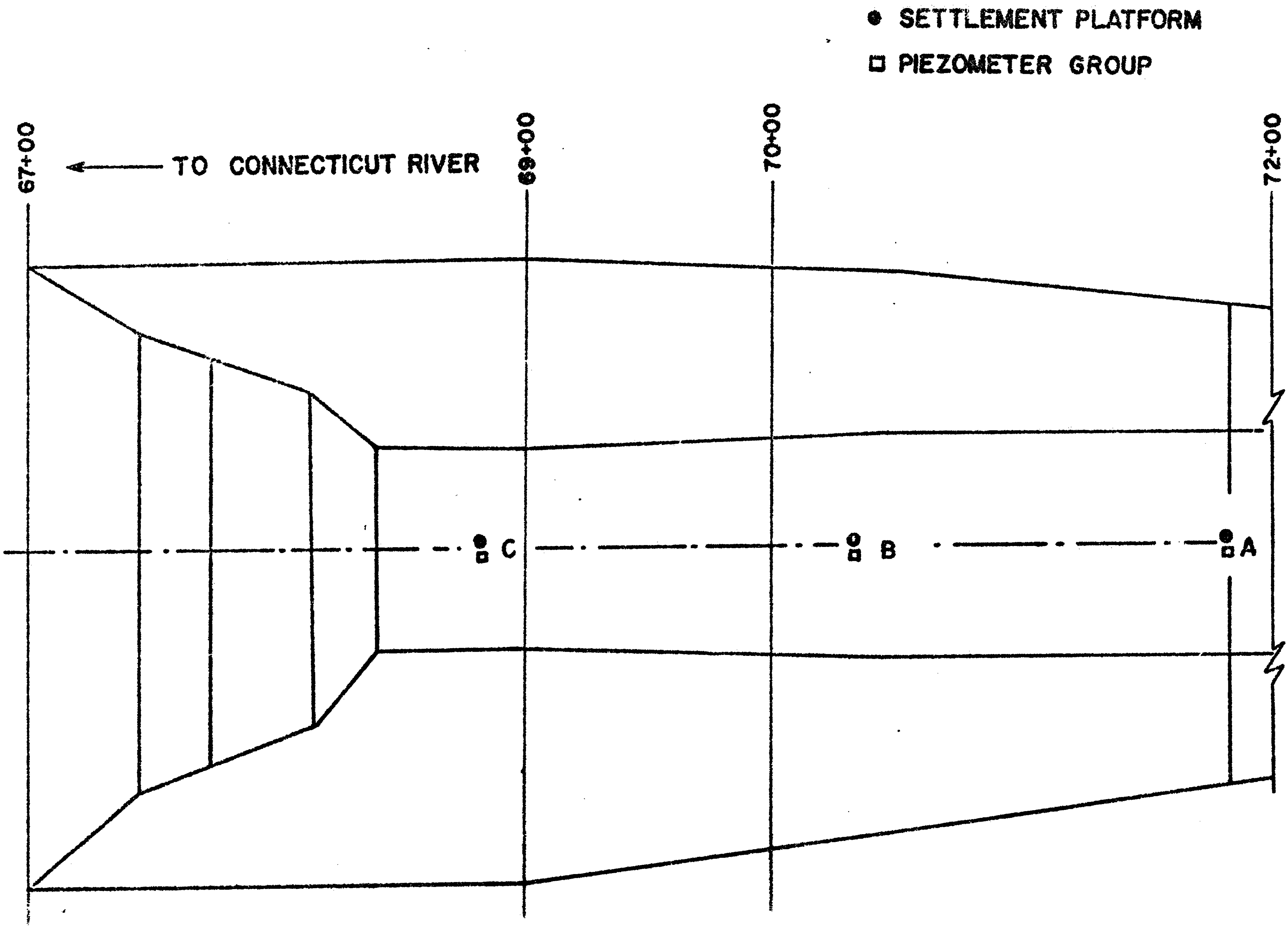
Figure 5 Reconstructed Hydrostatic-Excess-Pore Pressure Isochrones Near Settlement Platform 13 Near the Charter Oak Bridge.

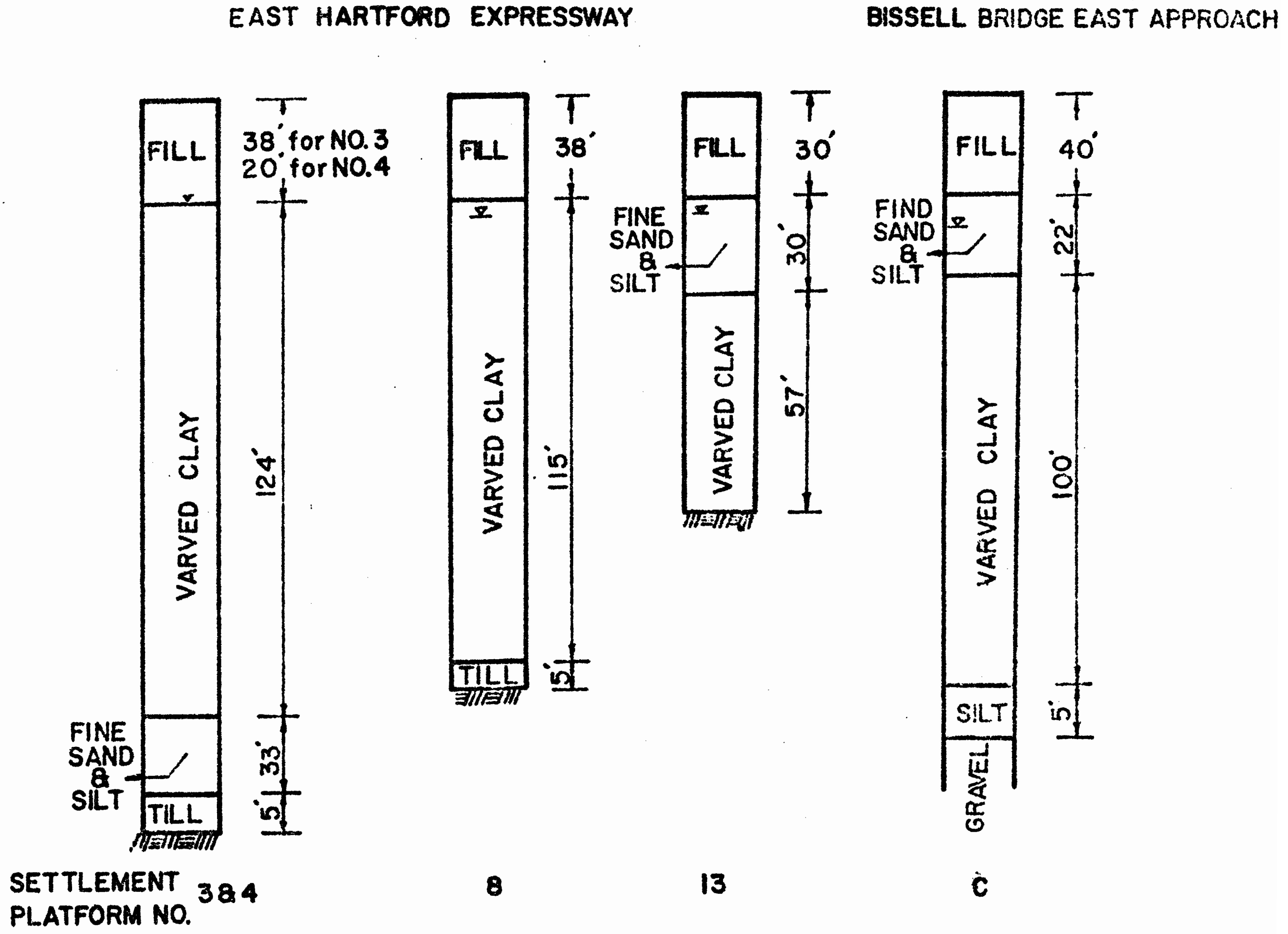
Figure 6 Square-Root of Adjusted-Time Plot of Settlement Observation on Platform 13 Near Charter Oak Bridge.

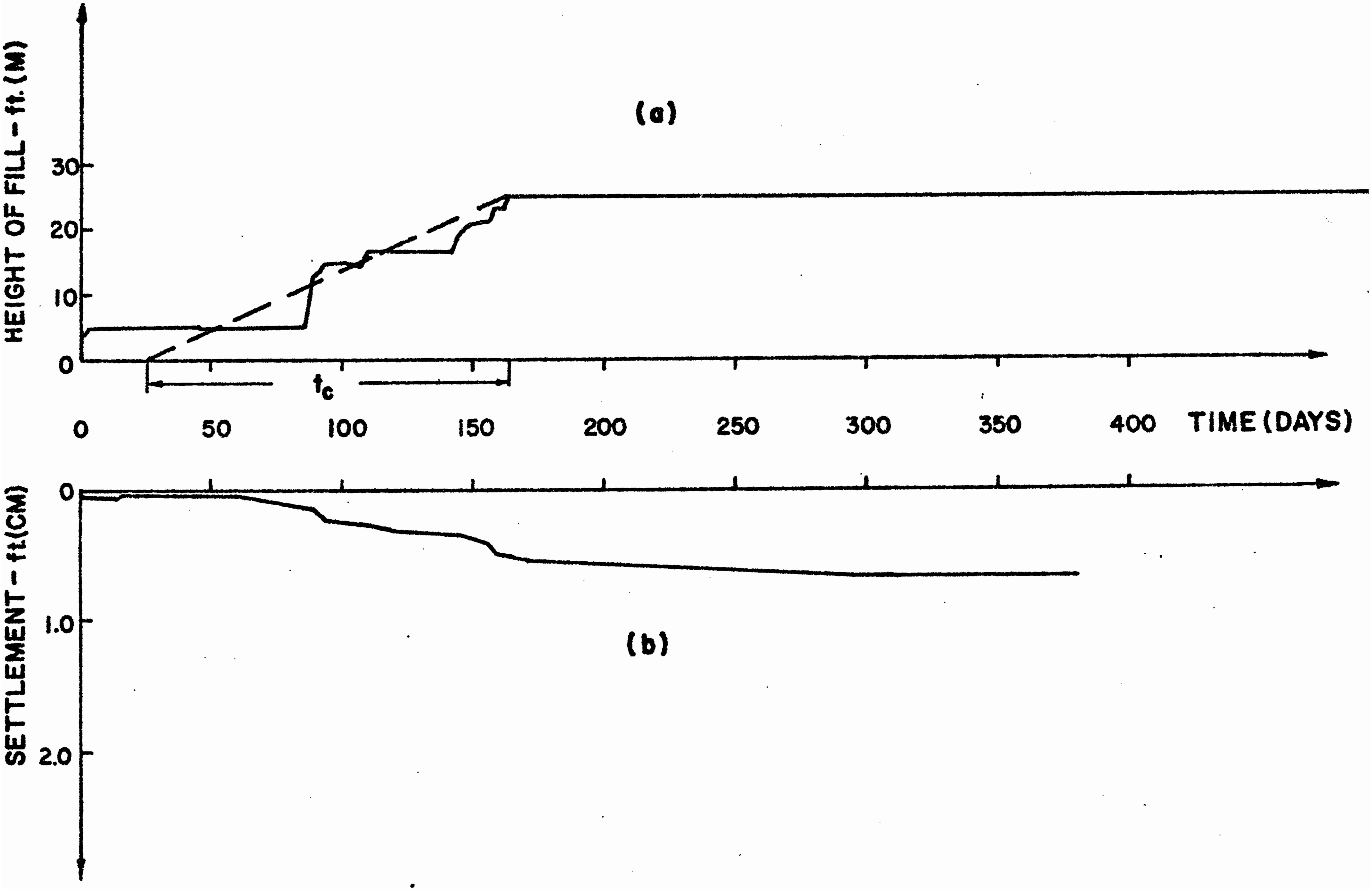
Figure 7 Pseudo-Two Dimensional Consolidation Model Used in Analysis.



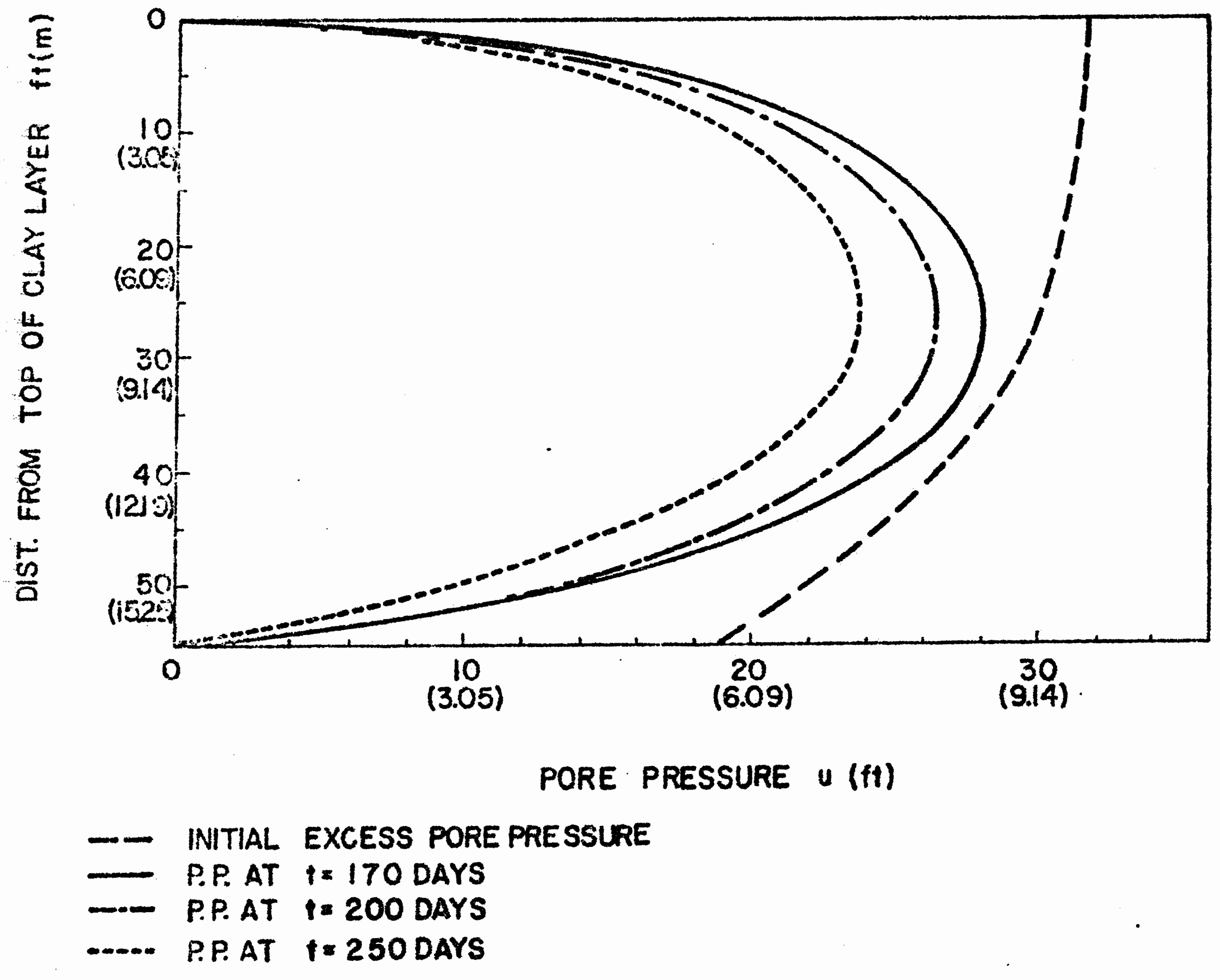
CONNECTICUT RIVER
Relocation of Willow Brook
Colt Street
Low St. Ext.
Box Culvert
3
4
8
33" R.C.P.
CHARTER OAK BRIDGE
West Service Road & Relocation-Hockanum River
H.E. LT. Co. Service Rd.
13
HOCKANUM RIVER
• — PIEZOMETER GROUP
• — SETTLEMENT PLATFORM

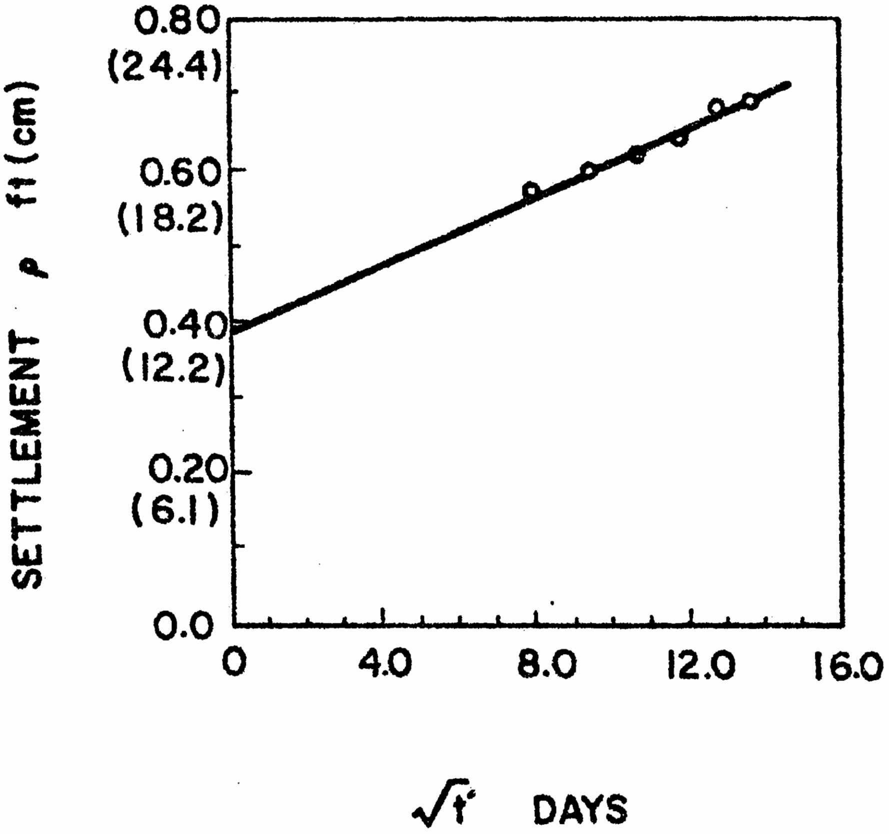

● SETTLEMENT PLATFORM
□ PIEZOMETER GROUP
67+00
← TO CONNECTICUT RIVER
69+00
70+00
72+00
C
B
A

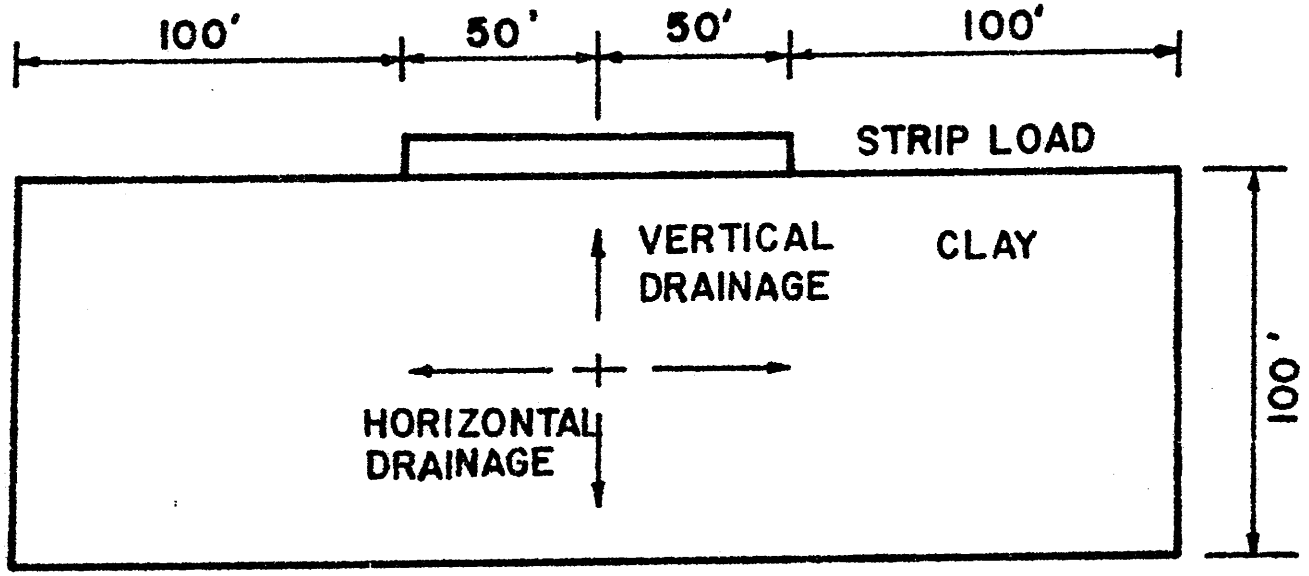

EAST HARTFORD EXPRESSWAY
BISSELL BRIDGE EAST APPROACH
FILL
VARVED CLAY
FINE SAND & SILT
TILL
38' for NO.3
20' for NO.4
124'
33'
5'
FILL
VARVED CLAY
TILL
38'
115'
5'
FILL
FINE SAND & SILT
VARVED CLAY
30'
30'
57'
FILL
FIND SAND & SILT
VARVED CLAY
SILT
GRAVEL
40'
22'
100'
5'
SETTLEMENT PLATFORM NO.
3&4
8
13
C



HEIGHT OF FILL - ft. (M)
30
20
10
0
(a)
t_c
0
50
100
150
200
250
300
350
400
TIME (DAYS)
SETTLEMENT - ft.(CM)
0
1.0
2.0
(b)


0
10
(3.05)
20
(6.09)
30
(9.14)
40
(12.19)
50
(15.24)
DIST. FROM TOP OF CLAY LAYER ft(m)
0
10
(3.05)
20
(6.09)
30
(9.14)
PORE PRESSURE u (ft)
INITIAL EXCESS PORE PRESSURE
P.P. AT t= 170 DAYS
P.P. AT t= 200 DAYS
P.P. AT t= 250 DAYS


0.80
(24.4)
0.60
(18.2)
0.40
(12.2)
0.20
(6.1)
0.0
SETTLEMENT ρ ft (cm)
0
4.0
8.0
12.0
16.0
√t DAYS



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MODEL USED FOR CONSOLIDATION
UNDER VERTICAL AND HORIZONTAL
PORE PRESSURE DISSIPATION