Evaluation of the Horizontal Coefficient of Consolidation Determined by One Dimensional Consolidation Tests for Soft Saturated Soil

José A. García Betancourt
Civil Engineering
Omaira Collazos, Ph.D.
Civil and Environmental Engineering Department
Polytechnic University of Puerto Rico

Abstract *— When determining time of consolidation at a project site where a soft clay soil profile is present the coefficients of vertical and horizontal consolidation are key parameters, when vertical drains are used. The coefficient of vertical consolidation,* c_v*, can be obtained with a consolidation test. The horizontal coefficient of consolidation,* c_h*, is typically estimated or determined by field tests. For this project the* c_h *value was obtained by consolidation laboratory test. Ten consolidation tests were performed on five samples obtained at different sites in Puerto Rico. Five consolidation tests were performed to provide vertical drainage and the other five were performed so radial drainage would be provided. The experimental results were compared to empirical values provided by the Federal Highway Authority of Transportation. Values of* c_h*, can be assumed to be equal to 1 to 2 times the* c_v *value and would be a conservative value to determine the time of consolidation for a given project. Further field studies such as trial embankments may be performed to better understand the effect of the soil profile to the values of* c_h*.*

Key Terms *— Drains, Horizontal Coefficient of Consolidation, Saturated Clays, Vertical Coefficient of Consolidation.*

INTRODUCTION

The vertical coefficient of consolidation (c_v) is defined as the rate to which a saturated clay soils settles due to a specific axial loading. The knowledge of this parameter is of very important when construction over a compressible soil layer is encountered and a deep foundation system is not a feasible alternative. The value of c_v can be determined by performing a one dimensional consolidation test to an undisturbed sample. To improve soils with the aforementioned condition geotechnical engineers would propose preloading with the use of vertical drains as an alternative.

When using vertical drains, a parameter known as the horizontal coefficient of consolidation is needed to calculate the estimated time of consolidation. To determine this parameter a field test may be performed (i.e. trial embankment), however many contractors do not find this feasible due to time consumption and cost. Geotechnical engineers may estimate this value based on experience and several empirical relationships.

The project proposes to compare theoretical values, as it would be obtained using relations from Federal Highway Report No. FHWA RD-86/168, and consolidation tests that will have the load application in the horizontal direction.

All of the undisturbed samples used for this study were obtained by an independent geotechnical consulting firm and are from several locations in Puerto Rico. The tests were performed on one sample from Naguabo, one from Humacao, one from Aguada and two from Dorado at varying depths. Both coefficients of consolidation will be determined and compared between theoretical and experimental values.

THEORETICAL BACKGROUND

To understand this concept, one must have basic knowledge of soil consolidation theory and preloading procedures. This will be discussed in the following sub-sections: consolidation theory with emphasis in the coefficients of consolidation, tests, preloading with vertical drains

Consolidation Theory

Soil Compressibility is due to stress increases by soil foundations, surcharge or other loads that may be added to. Compression can be caused by deformation and relocation of soil particles or expulsion of water or air from the void spaces in soil. Settlement of soils can be divided into three major categories; immediate settlement, which typically occur in dry or saturated soils without change in moisture content. It is based on the theory of elasticity. Primary consolidation settlement, which is caused by expulsion of water that occupies voids in saturated cohesive soils; and secondary consolidation settlement is seen in saturated cohesive soils and is a re-arrangement of the soil particles [1].

When a load is applied to a soil layer an increase in pore water pressure occurs. For granular soils water dissipates much more rapidly than in fine cohesive soils hence the immediate settlement and primary consolidation settlement for granular soils is virtually the same. However, for fine grained soils primary consolidation takes much longer due to the slow rate of dissipation that occurs for this type of soil, thus primary consolidation will occur much longer after the immediate settlement. When a soil layer that covers a large area is loaded vertically, (surcharge, foundations) compressibility can be assumed to occur in one direction (one-dimensional consolidation) [2].

One Dimensional Consolidation Test

The consolidation test was performed using the standard test method D2435 of the American Standards Test Methods (ASTM) [3]. This test method determines the magnitude of consolidation and consolidation rate of a laterally confined specimen by draining the specimen with the application of an axial load. This method is performed typically on fine grained soils (silty and/or clayey) in an undisturbed state. These samples are obtained by sampling with 3 inch diameter shelby tubes. These then are cut to size to fit in the oedometer cell where the incremental loading schedule will be applied as shown Figure 1.

The data obtained from consolidation test can be used to estimate settlement that may occur to a foundation or structure. Also, it is possible to estimate the relationship between the effective stress and void ratio or strain, and the rate of consolidation by evaluating the coefficient of consolidation. As mentioned above, the soil specimen is restrained laterally and shall is loaded axially. The applied stress increment is maintained until the pore water pressure is dissipated. The stress to be applied are in function the stresses that the soil will experience due to the construction of proposed structures.

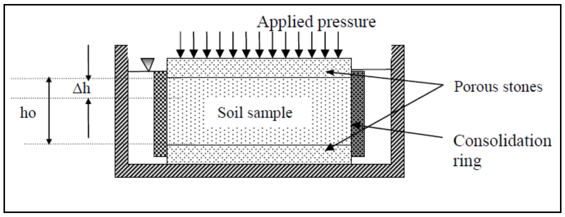

Figure 1
Schematic Diagram of Oedometer Cell

The test is performed assuming the following: the soil is homogeneous and saturated; the dissipation in pore water flow is in vertical direction; stress-strain relationship is linear over the load increment; ratio of permeability and compressibility is constant over the load increment; and Darcy's law for flow through porous media is applicable.

For this investigation vertical and radial (horizontal) coefficient of consolidation will be determined. The coefficient of consolidation is defined as the rate to which compression occurs in a particular soil by dissipation of pore water pressure. The vertical coefficient of consolidation is determined by the Casagrande's logarithm of time method [5]. In order to determine the horizontal coefficient of consolidation tests are carried out in accordance with ASTM D2435. The only difference would be that the specimen would be cut horizontally. The shelby tube sample was laid in a horizontal direction and cut with the consolidation ring as shown in Figure 2.

Figure 2
Example of Cutting Sample for Consolidation with Allowing Radial Drainage

Vertical and Radial Soil Compression

Simple preloading consists of placing a temporary surcharge over a soft soil deposit in order to achieve the consolidation. Preloading reduces settlement and differential settlements that occur as a result of increase in vertical stress due to new structures. The water dissipated pore pressure is dissipated in a vertical direction when this method is used as shown in Figure 3[6]. In order to obtain radial drainage, vertical drains may be installed.

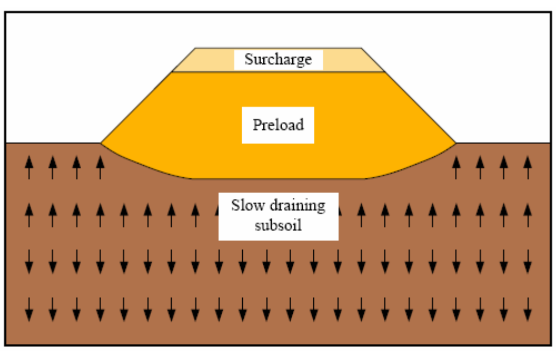

Figure 3
Schematic of Vertical Drainage with no Drains

The vertical drains accelerate the consolidation process and also help to prevent any bearing failure that may occur due to the placement of fill. Vertical drains accelerate primary consolidation (dissipation of pore water pressure) and have little or no effect on the secondary consolidation. Vertical drains may be installed with sand columns or geosynthetic drains.

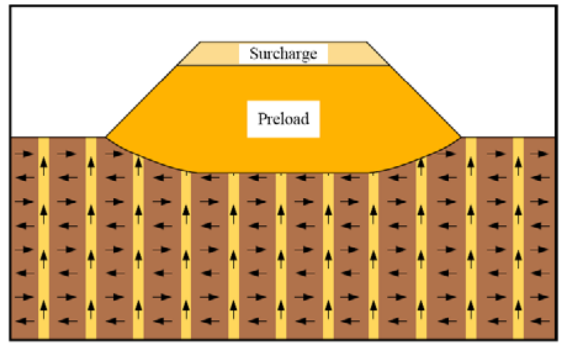

Figure 4
Schematic of Vertical Drainage with Drains

To find the settlement without drains Equation (1) can be applied where: s(t) is the settlement at any time, U is the average consolidation and S(c) is the primary consolidation settlement. The U value is determined in function of the time factor T_v (2).

To determine time of settlement with vertical drains Barron's equation for the simple method may be applied (3) [7] where: D is the drain influence zone, c_h is the coefficient of consolidation, d_w is the drain diameter, and U_h is the average degree of consolidation due to horizontal drainage..

$$s_t = U_v s_f \quad (1)$$

$$T_v = c_v t/L^2 \quad (2)$$

$$t = (D^2/8c_h)\,(\ln(D/d_w)-0.75)\,(\ln(1/(1-U_h))) \quad (3)$$

Notice that both coefficients of consolidation (vertical and radial) are important parameter when determining time of consolidation. Nomograms to determine rate of settlement and time are available from the FHWA [7].

Coefficient of Horizontal Consolidation

The coefficient of horizontal consolidation is needed for the design of vertical drains. This value is not part of routine investigations and may be evaluated using several methods as shown in Table 1 [2].

Table 1
Determination of c_h, Horizontal Coefficient of Consolidation

Where Done	Test	Comments; references
Lab.	Std. Consolidation or Triaxial Test	Modify equipment to provide radial drainage or cut specimen appropriately. Escario and Uriel (1961)
Lab.	Special (Rowe cell)	Rowe and Barden (1975)
In Situ	Piezocone	Torstensson (1975)
In Situ	Permeability test	Constant or falling head tests yield permeability, from which c_v and c_h can be calculated. Wilkinson (1968)
In Situ	Consolidation	Clarke et al. (1979)
In Situ	Trial Embankment	Interpretation of piezometer reading:: Johnson (1970). Interpretation of field settlement records: Asaoka (1978) Magnan and Deroy (1980), Magnan and Mieussens (1980)

This coefficient is also calculated by using an Equation (4) as shown by the FHWA, Table 2 [7].

$$c_h = (k_h/k_v)c_v \qquad (4)$$

Equation (4) establishes a relationship between vertical and horizontal coefficients of consolidations and the ratio of horizontal and vertical permeability. FHWA notes that the ratios are provided for general purposes only and designers should verify the actual properties of any given soil.

Table 2
Representative ratios of k_h/k_v for soft clays

Item	Description	k_h/k_v= c_h/c_v
1	No evidence of layering (partially dried clay has completely uniform appearance)	1.2 +/- 0.2
2	No or only slightly developed macrofabric (e.g. sedimentary clays with discontinuous lenses and layers of more permeable soil)	1 to 1.5
3	Slight layering (e.g. sedimentary clays with occasional silt dustings to random silty lenses)	2 to 5
4	Fairly well to well developd macrofabric (e.g. sedimentary clays with discontinuous lenses and layers of more permeable material)	2 to 4
5	Varved clays in Northeastern US	10 +/-5
6	Varved clays and other deposits containing embedded and more or less continuous permeable layers	3 to 15

Laboratory Tests

This section will describe the soil sampling and the test procedure.

Field Work

Soil samples were obtained by the use of an automatic drill rig CME 55. Extraction was performed with the use of shelby tubes that had a 3 inch diameter and were approximately 24 inches long as shown in Figure 5. Samples are from several sites throughout the island. Table 3 shows the location of each soil sampling, as well as the depth and characteristics of each soil.

Figure 5
Shelby Tube with Sample

Table 3

Determination of c_h, horizontal coefficient of consolidation

ID	Location	Description
1	Naguabo, PR	Depth 6 – 8 ft, Brown sandy silt. Sample is obtained in a clayey profile.
2	Humacao, PR	Depth 12 – 14 ft, Brown silty clay. Sample was obtained from a laminated profile(sand and silt).
3	Dorado, PR	Depth 18 – 20 ft, Very dark brown/black peat and clay. Sample was obtained from a laminated profile (sand).
4	Aguada, PR	Depth 16 – 18 ft, Dark brownish gray clay. Sample was obtained from a clayey profile.
5	Dorado, PR	Depth 22 – 24 ft, Dark gray clay. Sample was obtained from a laminated profile (sand).

Consolidation Tests

All of the samples were tested by a Geocomp Load Trac II machine for incremental consolidation loading. Figure 6 shows typical consolidation tests which were performed to all samples to obtain vertical consolidation properties.

To obtain horizontal consolidation properties the samples were cut such as the stress would be applied in a horizontal manner. This would restrict drainage in the vertical direction and allow radial flow.

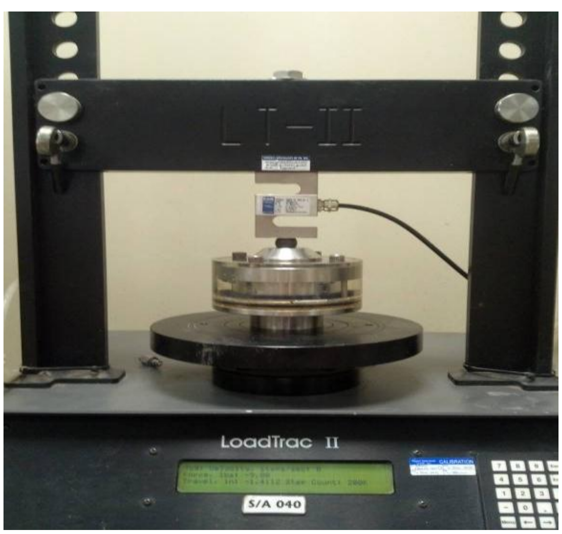

Figure 6

Geocomp Load Trac II Equipment

TEST RESULTS

All consolidation tests were performed using an incremental loading. The equipment used provides the plots and tables of the entire test using the software ICON [8]. The loading schedule included loading and unloading, as shown in Figure 7.

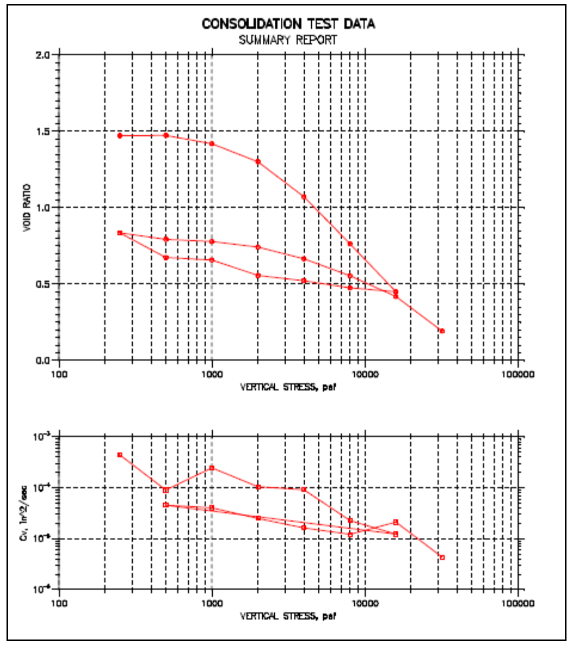

Figure 7

Consolidation Test Results Example, Sample 3

From the tests the coefficients of vertical and coefficients of horizontal consolidation were obtained. As previously mentioned, the horizontal coefficient of consolidation is obtained by cutting the sample in a way that radial drainage will occur.

Tables 4 – 7 summarize the results obtained from this test. The stresses used for comparison were 500 psf, 1000 psf, 2000 psf and 4000 psf.

Table 4

Coefficients of Consolidation 500 psf

Sample ID	c_v	c_h	$k_h/k_v= c_h/c_v$
1	8.12e-04	1.24e-03	1.53
2	1.37E-04	7.47E-05	0.55
3	1.03E-04	9.04E-05	0.88
4	8.86E-05	7.29E-05	0.82
5	3.72E-04	1.47E-05	0.04

Table 5
Coefficients of Consolidation 1000 psf

Sample ID	c_v	c_h	$k_h/k_v= c_h/c_v$
1	1.20E-03	1.18E-03	0.98
2	2.54E-04	2.64E-04	1.04
3	2.13E-04	2.47E-04	1.16
4	1.12E-04	5.71E-05	0.51
5	1.31E-04	3.27E-04	2.50

Table 6
Coefficients of Consolidation 2000 psf

Sample ID	c_v	c_h	$k_h/k_v= c_h/c_v$
1	7.55E-04	5.52E-05	0.07
2	4.25E-04	2.25E-04	0.53
3	1.05E-04	1.05E-04	1.00
4	1.02E-04	3.72E-05	0.36
5	5.80E-05	1.37E-04	2.36

Table 7
Coefficients of Consolidation 4000 psf

Sample ID	c_v	c_h	$k_h/k_v= c_h/c_v$
1	1.80E-04	6.39E-04	3.55
2	2.16E-04	1.82E-04	0.84
3	3.02E-05	9.17E-05	3.04
4	8.79E-05	2.05E-05	0.23
5	2.73E-05	5.78E-05	2.12

The vertical coefficient of consolidation obtained from the tests will be compares with the relationship provided by FHWA.

Conclusions

For the samples tested approximately 50% of the calculated ratio, c_h/c_v, is greater than one. Previous studies have demonstrated that the coefficient of horizontal consolidation is typically equal to or greater than the vertical coefficient of consolidation [7]. For three samples the ratio was below 0.50 for a given load as shown in Tables 4 to 7.

The highest ratios obtained were 3.55 and 3.04 for sample 1 and 3 for a pressure of 4000 psf respectively. This high ratio could be evidence that the ratio may tend to be higher when a stresses above 4000 psf are applied. Values of c_h which vary from 1 to 2 times the value c_v and would be a conservative estimate to determine the time of consolidation. Figure 8 shows the ratios between vertical and horizontal coefficients of consolidation. A similar tendency is observed for all of the applied stresses except for the stress of 4000 psf.

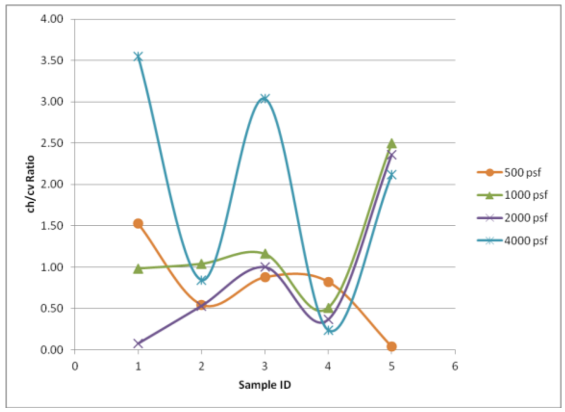

Figure 8
Coefficient of Consolidation Ratios

The values provided by the FHWA [5] have to be used carefully since in some cases they recommend to use c_h values as high as 15 times c_v. This assumption for specific site conditions, such as laminated and layered soil profiles, which are not possible to simulate in one dimensional consolidation test [3]. Nevertheless, the theoretical values of c_h should be used for general information purposes only and actual field test should be performed.

Recommendations and Future Works

It is important to evaluate the soil behavior at larger stresses. Larger stresses may also be evaluated to see if higher ratios are obtained such as for the 4000 psf stress.

Since the samples were obtained from active sites, field tests, such as trial embankments [6], may be performed to confirm the experimental results. This can also assist in a better understanding of how the existing soil conditions (soil profile) may affect the value of the horizontal coefficient of consolidation.

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