Comparison of results of pre-consolidation of soft soil using analytical and finite element software.

Muhammad D Abdulnafaa1, Ayman W Al-Dabbagh1, and Mohammed S Mahmoud1

1Department of Environmental Engineering, Engineering College, Mosul University, Mosul, Iraq
Email: moh_msc2006@yahoo.com

Abstract This paper targets to make a comparison between consolidation calculation for softy soil layer by two methods, by using usual analytical equations found in most soil mechanic books, and PLAXIS simulation. The second method used a finite elements method represented by PLAXIS program, with the same parameters that were used in the first method, and other default parameters necessary in PLAXIS calculations. The results show strong agreement between the two methods, especially in the Active and excess pore water pressure, total and effective stresses, and total settlement in soft clay soils. In another hand, a significant difference in the values of time of consolidation calculated by the two methods is observed. These differences appeared due to using many different equations to calculate the (cv) consolidation coefficient.

1. Introduction

1.1 PLAXIS
PLAXIS is a finite element program in which soil models are designed to simulate the soil behavior for geotechnical applications. The soil models have been presented by PLAXIS code and have been developed with great care. Even though many experimental works and corroborations have been accomplished, it cannot be ascertained that the results of PLAXIS program don’t have any errors [1]. Furthermore, the imitation of geotechnical problems by means of the finite element method implicitly involves some unavoidable numerical and modeling errors. The precision at which reality is approximated depends highly on many factors:
1- The proficiency of the user to concern the modeling of the problem.
2- The understanding of the soil models and their boundary condition.
3- The selection of model parameters.
4- The capability to determine the reliability of the computational results [1].

All these reasons led to some differences in the results of geotechnical outputs of any finite element program like PLAXIS compared with normal analytical methods (Terzaghi’s equations) used in calculations.

1.2 Preloading
The procedure of compression of soil under the use of vertical load, before actual construction i.e. placement of final construction load, is known as preloading. Generally, there are two types of Preloadings. I) Conventional preloading – like embankment. II) Vacuum preloading [2]. Preloading is the application of surcharge load (temporary load) on the site prior to construction of the enduring structure until most of the primary settlement has occurred as shown in Figure 1 [3, 4]. The objective of preloading and pre-consolidation in soft soil is to reduce the settlement when real construction takes place at the site. This ultimately condenses the risk of collapse/ flaw/damage in the structure, resulting from the differential settlement, which is of main importance in engineering construction. Increasing the time of preloading or magnitude of preload can be reduced or eliminated in the secondary settlement. This increase can be achieved by application a surcharge higher than the working load and the soil will be over-consolidated. This over-consolidated soil has less secondary consolidation than the normally consolidated soil, which finally is of advantage in geotechnical design at later stages as
shown in Figure 2. [5]. Was the first who presented vacuum preloading to accelerate consolidation. In vacuum consolidation, the surcharge load was replaced by atmospheric pressure as shown in Figure 3.

![Figure 1](image1.png)

**Figure 1.** Schematic of preloading of soft soil by conventional surcharge load

![Figure 2](image2.png)

**Figure 2.** Load-time-settlement with and without preloading

![Figure 3](image3.png)

**Figure 3.** Schematic of preloading of soft soil by vacuum surcharge load

Researchers have studied the preloading of soft soil using two types of preloadings. [6] Deals with the conventional preloading in order to study the practical considerations for using vertical drains in soil improvement projects. After that, [7] estimated the degree of consolidation for vacuum preloading Projects. [8] Studied soil improvement for a storage yard using the combined vacuum and fill the preloading method. However, most of the previous studies have primarily concentrated on using Vacuum Preloading with the sand drain to improve the soft soil [9], [10], [11] and [12]. This study
aims to make a comparison between analytical method and special software (PLAXIS) for calculation of consolidation characteristics in preloading of soft soil.

2. Materials and methodology

2.1 The description and geometry of embankment mode

The geometry of the embankment model in this study is shown in Figure 4. The top and base widths are equal to (20m) and (50m), respectively, so that, the side slope horizontal: vertical is equal to (1:3). The depth of the soft clayey soil layer is equal to (5m). The water table level at the surface of the soft clay layer.

The embankment consists of sandy silt soil (fill material). The softy soil consists of compressible clayey soil with high plasticity. Between the two soils, a thin layer of sand (0.25 cm) is put, to separate the layers and to work as a drain to collect the water from the underlying soft soil. A deep dense sand layer assumed to be under the soft soil. The deformation of this soil presumed to be zero. Hence, this layer is not included in the model and the fixed base is used instead. The properties of the compressible clay layer are taken from a real site [3]. The density of the fill materials, used as surcharge load, is assumed as a reasonable value for calculation. Some suitable values of the properties of the dense sand taken from the literature, are assumed for only the finite element analysis. The properties of the three soil layers are shown in Table 1.

| Parameter                  | Fill material | Sand Separating layer | Soft Clay                  |
|----------------------------|---------------|-----------------------|----------------------------|
| Material model             | Model Type    | Mohr-Coulomb Drained  | Mohr-Coulomb Drained      |
| Type of behavior           |               |                       |                            |
| Modulus of elasticity      | MPa           | 300                   |                            |
| Poisson’s Ratio            | 0.35          | 0.3                   | 0.35                       |
| Saturated unit weight      | kN/m³         | 20.0                  | 22.0                       | 15.27                      |
| Unsaturated unit weight    | kN/m³         | 18.0                  | 18.0                       | 15.5                       |
| Cohesion                   | kN/m³         | 2.0                   | 1.0                        | 35                         |
| Internal friction angle    | Degree        | 32                    | 35                         | 27                         |
| Dilatation angle           | Degree        | 0                     | 0                          | 0                          |
| Consolidation type         |               |                       | Normal consolidation       |
| Initial void ratio         |               |                       |                            |
| Compression index Cc       |               |                       |                            |
| Coefficient of             | m²/year       |                       |                            |

Figure 4. Schematic of the geometry of the embankment and softy clay layer
From a stability point of view, it is better to construct the embankment in stages [2]. Therefore, in this study, the construction of embankment consists of two phases, each phase taking 10 days. After the first phase, a consolidation period of 180 days is introduced to allow the excess pore pressures to dissipate. After the second construction phase, another consolidation period is presented from which the final settlement may be determined. Therefore, the four calculation phases have to be defined.

2.2 Assumptions of analytical solution using settlement equations

The settlement equations used in the analytical solution are dependent on [13]. Firstly, to solve the problem, the properties of the soil must be determined. From Table 1 and Figure 4 it can be shown that:

1- As the width of the embankment is 50m, and the length is too long (perpendicular on the paper), and point A at mid of clayey layer. Consequently, the surcharge fill can be considered, with some estimation, as infinite loading.

2- The procedure of solution includes finding the first settlement, which happened at the end of the first consolidation period (180 days). After the first construction stage, the total settlement after the second construction stage is found with its time.

3- To find the settlement of soft clay layer is divided into two layers (3 and 2 m). The settlement is founded by the summation of the settlement calculated in the center of each layer.

4- The properties of clayey layer taken are from the real site [2].

5- The separating sandy layer does not include in this solution because it has a little effect on the results and can be neglected.

6- The drainage from two sides, upper and lower limits.

7- Due to the assumptions and estimation taken in paragraphs (1 -7) above, the results may contain some estimation.

The equations used in the analytical calculations of consolidation were:

\[ S_{total} = \frac{c_c}{1+e_o} H \log \frac{\sigma_{zc}}{\sigma_{zo} + \Delta \sigma_z} + \sigma_{zc} + \Delta \sigma_z \quad \ldots \ldots (1) \]

\[ T_v = \frac{c_v t}{H^2} \quad \ldots \ldots (2) \]

\[ k = c_v m_v \gamma_w \quad \ldots \ldots (3) \]

Where \( S_{total} \) is total settlement (m) of embankment at the end of consolidation, \( c_c \) is the compressibility index of soft soil, \( H \) is the thickness of the soft soil layer (m), \( e_o \) is the initial void ratio, \( \sigma_{zc} \) is the overburden pressure of soft soil layer and \( \Delta \sigma_z \) is the additional pressure due to the construction of the embankment.

\( T_v \) is the time factor, \( t \) is the time (days), and \( c_v \) is the coefficient of consolidation (m²/day).

\( K \) is the hydraulic conductivity (m/day), \( m_v \) is the coefficient of volume change (m³/kN), and \( \gamma_w \) is the unit weight of water (kN/m³).

2.3 Solution using PLAXIS software (Finite Element Analysis):

Firstly, the geometry of the embankment model has been created as mentioned before in Figure 5. The PLAXIS program was used for finite element analysis of the embankment model. Plane strain analysis was carried out using the Mohr-Coulomb criterion for modeling of the soil behavior. The material properties required for calculations using this model as shown in Table (1). The modules of elasticity used in this case to give the value of the coefficient of consolidation (Cv) equal to that used in the analytical solution. As the equation used to calculate (Cv) in PLAXIS depends on the Modulus of elasticity and coefficient of permeability as shown by equations 4 and 5 [1].

\[ C_v = \frac{k E_{oed}}{\gamma_w} \quad \ldots \ldots (4) \]

\[ E_{oed} = \frac{E(1-v)}{(1+v)(1-2v)} \quad \ldots \ldots (5) \]
A very fine finite element mesh was used for all calculations and this mesh consisted of (811) elements. Using the 15-node triangular element the number of the nodes was equal to (6687) nodes, and (9732) number of stress points. The average element (side) size was equal to (0.7895m). The embankment mesh is shown in Figure 6. The initial condition for the model included two parts; one of them is to create water pressure Figure 7. The other part is to create initial stress for the soft clay soil, Figure 8.

The calculation using this program done in the staged construction phases, except for the last phase, which minimum pore pressure was used for the purpose of the total consolidation calculation. The consolidation type of calculation was drained condition for all materials and for all phases.
3. Results and discussion

3.1 Analytical solutions results

The analytical solution was adopted using equations 1, 2, and 3. The amount of settlement at the end of the first consolidation period (180) days was about (0.35 m). This amount of consolidation represented about (40%) of the total settlement (0.88m) for the load coming from the embankment at the first stage of construction. After the second construction stage, which took (10) days, the total settlement was about (1.18m). The amount of total settlement for the conditions of the embankment will reach after about (2520 days=7.0 years). The high value of settlement is due to the high value of the void ratio. The coefficient of conductivity K was \((4.741\times10^{-8} m/min=0.00068 m/day)\) for soft soil. The calculation of the above consolidation values was done using soft soil and embankment properties used in the consolidation equation.

3.2 PLAXIS solutions results

3.2.1 Active & excess pore water pressure in soils. PLAXIS program used to study the difference in pore water pressure after loading by an embankment of filling material. The active and excess pore water pressure are shown in Figures (9) and (10). In figure (9), the active pore water pressure returns to about the same values after the finish of the most settlement due to embankment load. The completion of the settlement in the PLAXIS can be confirmed by observing Figure (10), which shows that the excess pore water pressure was completed at the end of the settlement and returned to near zero. Figures (11) and (12) show respectively the development of active and excess pore water pressure with the time at point A which has a location at the mid-layer of soft clay, at the center of the embankment. It could be seen from Figure (11) that the active pore pressure at point (a) starts with about 25 kN/m² value, which represents the calculated value from the analytical results. With time, the active pore pressure increased until it reaches a maximum value after 30 days, due to increase in excess pore water pressure before the seepage of water to the sand drain. After that, with the seepage of water, the excess pore water starts to flow out with the settlement of soil to the end of the first stage (after 180 days) and the active pore water returns back to the initial value. The same path of active pore water pressure is observed in the second stage of loading. Figure (12) shows the same behavior of excess pore water pressure with time dropping down to the initial zero value at the end of the total settlement. The results show a notable difference in the time of the end of total settlement between the analytical and PLAXIS simulations because of use of different equations (3, 4, and 5) to calculate the \((c_v)\) the coefficient of consolidation.
Figure 9 Active pore pressures in the bottom of soft clay at the end of the preloading process

Maximum active pore pressure in the bottom of soft clay \( \approx 50 \text{ kN/m}^2 \)

Figure 10 Excess pore pressures in the bottom of soft clay at the end of the preloading process

Excess pore pressure in the bottom of soft clay \( \approx 0 \text{ kN/m}^2 \)

Figure 11 Variation of active pore pressures with time for point A at the middle of the soft clay layer
3.2.2 Total and effective stresses in soil.

The total and effective stresses developed in soils after loading stage are shown in Figures (13) and (14), respectively. It is shown that the difference between maximum total and effective stresses is about (50 kN/m²), which represents the active pore pressure in clay soil. These values of pressures in the soil, given by the PLAXIS model, represent logical values as shown in equations 6 and 7, which match with the analytical solution.

\[
\sigma_{\text{total}} = \gamma_m \times h, \text{ at end of soft soil }, \sigma_{\text{total}} = (5 \times 18) + (5 \times 15.2) = 166 \text{ kN/m}^2 \ldots (6)
\]

\[
\sigma_{\text{effective}} = \gamma_{\text{eff.}} \times h, \text{ at end of soft soil }, \sigma_{\text{eff.}} = (5 \times 18) + (5 \times (15.2 - 10)) = 116 \text{ kN/m}^2 \ldots (7)
\]
3.2.3 Deformation (consolidation) of soil due to loading (displacements of soil)

Because of applied surcharge loading (embankment) to soft clay soil, the consolidation (vertical displacement) will happen in soft clay soil and will appear in the program as deformation as shown in Figures (15 and 16). The maximum vertical displacement in the soil, after the fourth phase, is (1.33m) which represents the total settlement in the bottom of soft clay soil, while the settlement from the analytical solution is about (1.2m) as shown in figures (15 and 16). The results show reasonable agreement between the analytical and PLAXIS simulations.

---

**Figure 14** Maximum effective principal stress in the bottom of soft clay

**Figure 15** Maximum vertical displacement (settlement) in the bottom of soft clay

**Figure 16** Deformed mesh for embankment model and soft soil

Maximum effective principal stress in the bottom of soft clay ≈ 114 kN/m²

Maximum settlement in the bottom of soft clay ≈ 1.33 m
4. Conclusions and recommendations

The comparison was done between the software and the analytical method of results of preloading of soft soil using embankment surcharge load. The current study contributes to our knowledge by addressing four important points in using analytical and finite element methods for the settlement of soft clay which is drawn as follows

1. The results suggest significant agreement between the values of Active and excess pore water pressure in soft clay soils, calculated by analytical and PLAXIS solutions.

2. The difference in time of consolidation, while the time for total consolidation in an analytical method for more than 2500 days. The consolidation time using PLAXIS program was not more than 400 days, due to use of different equations (3, 4, and 5) to calculate the \( c_v \) the coefficient of consolidation.

3. The results give an appropriate agreement between the values of total and effective stresses in soft clay soils, calculated by analytical and PLAXIS solutions.

4. The results give a remarkable matching between the values of total settlement in soft clay soils, calculated by analytical and PLAXIS solutions.

Further studies will be required to investigate the results of the real case of consolidation happening in field and compared the results with finite element simulation results.

References:

[1] Brinkgreve R 2002 PLAXIS (version 8) user’s manual. Delft University of Technology and PLAXIS BV, Netherlands

[2] Bhattacharya A and Basack S 2011 Review of the use of the pre-loading technique and vertical drains for soil consolidation, Proceedings of Indian Geotechnical Conference December 15-17, Kochi (Paper No. H-029)

[3] Radhakrishnan G, Kumar M, Raju G, Prasad D and Venkateswarulu D 2010 Study of Consolidation Accelerated by Sand Drains

[4] Stapelfeldt T 2006 Preloading and vertical drains. Electronic publication, http://www.tkk.fi/Yksikot/Rakennus/Pohja/Preloading_and_vertical_drains.pdf.

[5] Kjellman W 1952 Consolidation of clay by means of Atmospheric Pressure. In Proceedings of a Conference on Soil Stabilization Boston: MIT Press (Vol. 2582263)

[6] Chu J, Bo M and Choa V 2004 Practical considerations for using vertical drains in soil improvement projects, Geotextiles and Geomembranes 22, 1, 101-117.

[7] Chu J and Yan S 2005 Estimation of degree of consolidation for vacuum preloading projects, International Journal of Geomechanics

[8] Yan S and Chu J 2005 Soil improvement for a storage yard using the combined vacuum and fill preloading method. Canadian Geotechnical Journal, 42(4), 1094-1104

[9] Chu J, Yan S and Yang H 2000 Soil improvement by the vacuum preloading method for an oil storage station, Geotechnique, 50(6), 625-632

[10] Yan S and Chu J 2003 Soil improvement for a road using the vacuum preloading method. Proceedings of the ICE-Ground Improvement, 7(4), 165-172

[11] Tang M, Shang J, Chu J, Yan S, Yang H, Almeida M, ... and Martins I 2004 Vacuum preloading consolidation of Yaoqiang Airport runway. Ground and Soil Improvement, 44

[12] Chai J, Miura N and Bergado D 2008 Preloading clayey deposit by vacuum pressure with cap-drain: analyses versus performance. Geotextiles and Geomembranes, 26(3), 220-230

[13] Das B 2013 Advanced soil mechanics CRC Press