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Assessment of recent methods for determination of soil final settlement using field data

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Abstract. The problem of soil consolidation was first studied by Terzaghi who formulated the well-known one-dimensional consolidation theory. However, this widely used method was found to provide poorly accurate estimations, since Terzaghi considered the assumption of constant permeability and consolidation coefficient. The poor accuracy is also due to the low resemblance between laboratory results and field actual measurements. In order to overcome this issue, many researchers proposed new approaches to estimate and predict soil settlement more accurately. Among these approaches, field-based methods are particularly promising. For instance, the Asaoka method (1978), Sridharan (1987) method, Tan (1995) method, Chunlin's method (2014), and recent methods of Guo et al. (2017, 2018b) and Guo et al. 2018(a,). This paper aims to assess and discuss the results of some recent methods using a field consolidation monitoring data set.

Introduction

The prediction of soil settlement has always been an issue in soil mechanics. Terzaghi (1948) formulated the famous one-dimensional consolidation theory, which revealed to be not that accurate in terms of estimating consolidation settlement, mainly because the coefficient of consolidation obtained in laboratory is usually different from the field value. Hence, many researchers attempted to propose new approaches in order to improve the accuracy of the prediction of soil settlement. In the beginning, many works focused on a way to determine a value of coefficient of consolidation that is close to the field value. For instance, the standard methods of Casagrande logarithmic of time fitting method and Taylor square root of time fitting method can be mentioned. More recently, promising approaches based on field monitoring data were proposed. The idea of using real field settlement data has been explored by Asaoka (1978), Sridharan (1987), Tan (1995), Chunlin (2014), Guo & Chu (2017) and Guo et al. (2018(a, b)). Asaoka's method which is based on Mikasa's consolidation theory uses the concept of linear regression. Tan's hyperbolic and Sridharan rectangular hyperbola methods are curve fitting methods that assume the curve $\boldsymbol{U_v}$ vs $\boldsymbol{T_v}$ ($\boldsymbol{U_v}$: degree of vertical consolidation, $\boldsymbol{T_v}$: vertical factor of time) as an hyperbolic curve. Chunlin's method is based on Terzaghi's 1-D consolidation theory which allows a better estimation of the settlement without using the initial consolidation. Guo & Chu (2017) and Guo et al. (2018(b)) proposed a method for predicting the soil final settlement using linear regression, by fitting the settlement curve to the Chapman–Richards equation. And more recently, Guo et al. (2018(a)) published a modification of the procedure of the hyperbolic method with a new chart.

Among all these new methods and approaches one can legitimately ask which one should be used, and in which situation.

This paper aims to show and share a comparison between Guo & Chu (2017), Guo et al. (2018(b)), and Guo et al.(2018(a)) methods, using a set of field soil settlement monitoring data. As a reference, Asaoka's method was also processed for the same data set.

Asaoka's method:
The method proposed by Asaoka (1978) is an observational procedure, in which the future settlement is predicted using previous settlement observations.
Asaoka adopted Mikasa's equation:

$$\dot{\varepsilon} = c_v \ \varepsilon_{zz} \tag{1}$$

$\varepsilon(t, z)$ is the vertical strain, where $\dot{\varepsilon} = \partial\varepsilon/\partial t$ and $\varepsilon_{zz} = \partial^2\varepsilon/\partial z^2$

By introducing two function of time, the solution of the previous equation is written as:

$$\varepsilon(t, z) = T + \frac{1}{2!}\left(\frac{z^2}{c_v}\dot{T}\right) + \frac{1}{4!}\left(\frac{z^4}{c_v^2}\ddot{T}\right) + \cdots + zF + \frac{1}{3!}\left(\frac{z^3}{c_v}\dot{F}\right) + \frac{1}{5!}\left(\frac{z^5}{c_v^2}\ddot{F}\right) + \cdots \tag{2}$$

Where c_v is the coefficient of vertical consolidation,$T = \varepsilon(t, z = 0)$ and $F = \frac{\partial}{\partial z}\ \varepsilon(t, z = 0)$.

By considering the two boundary conditions; drainage from both top and bottom boundaries, and upward drainage the following equations were derived:

For double drainage:

$$\delta + \frac{1}{3!}\left(\frac{H^2}{c_v}\dot{\delta}\right) + \frac{1}{5!}\left(\frac{H^4}{c_v^2}\ddot{\delta}\right) + \cdots = \frac{H}{2}\left(\bar{\varepsilon} + \underline{\varepsilon}\right) \tag{3}$$

Where :δ is the settlement, $\varepsilon(t, z = 0) = \bar{\varepsilon}$: constant and $\varepsilon(t, z = H) = \underline{\varepsilon}$: constant.

After neglecting the higher order differential terms, Asaoka (1978) adopted the following first order approximation:

$$\delta + c_1\ \dot{\delta} = C \tag{4}$$

Where $c_1, c_2, \ldots, c_n$ and C are unknown constants

By introducing discrete time $t_j = \Delta t\,.\,j$ with Δt : constant

Eq.4 can be expressed as:

$$\delta_j = \beta_0 + \beta_1\delta_{j-1} \tag{5}$$

Where δ_j and δ_{j-1} are the settlement at time j and j-1, β_0 and β_1 are unknown parameters.

When the settlement approaches its final value δ_{ult}, a stable state is observed which can be expressed as:

$$\delta_j = \delta_{j-1} = \delta_{ult} \tag{6}$$

Form Eq.6, when the values of δ_j are plotted against the values of δ_{j-1}, the final settlement δ_{ult} can be determined by identifying graphicly the intersection of the plot δ_j vs δ_{j-1} with the straight 45° line presented by the equation (y = x).

From Eq.5 and Eq.6 The final settlement can be predicted also by finding the values of β_1 and β_0 from the extrapolated plot, β_1 corresponding to its slope, and β_0 corresponding to the intersection with the ordinate axis. And then the final settlement can be calculated by substituting the values of β_1 et β_0 in Eq.5. this leads to the equation below:

$$\delta_{ult} = \frac{\beta_0}{1-\beta_1} \tag{7}$$

Hence, the settlement at time $t = \Delta t \cdot j$ can be expressed by the following equation

$$\delta_j = \frac{\beta_0}{1-\beta_1} - \left(\frac{\beta_0}{1-\beta_1} - \delta_0\right)(\beta_1)^j \tag{8}$$

The observational method of Guo et al.(2017,2018(b)) [5], [6]:
For vertical drainage, the relationship of U_v vs T_v from Terzaghi one dimensional consolidation theory, is given as (Terzaghi et al. 1996):

$$U_v = 1 - \frac{4}{\pi^2}\sum_{n=0}^{n=\infty}\frac{2}{(2n+1)^2}\exp(-M^2 T_v) \tag{9}$$

Where $M = (2n+1) \times \pi/2$, (n: integer)

T_v: The Factor of time ($T_v = c_v t/H^2$)

t : Consolidation time

H: the thickness of the layer

The equation for calculating the average degree of consolidation for pure horizontal drainage case was given by Hansbo (1981) as

$$U_h = 1 - \exp\left(-\frac{8T_h}{\mu}\right) \tag{10a}$$

Where the time factor is given by:

$$T_h = \frac{c_h t}{D^2} \tag{10b}$$

And μ:

$$\mu = \frac{n^2}{n^2-1}\log n - \frac{3n^2-1}{4n^2} \tag{10c}$$

n: drainage spacing ration D/d; D: diameter of an equivalent cylinder of soil influenced by each drain, $D = 1.13s$ for a square pattern and $= 1.05s$ for a triangular pattern (s: vertical drain spacing), d: diameter of a sand drain $d = 2(b + t')/\pi$ ($b = \text{width}, t' = \text{thickness of drain cross section}$).

Carrillo (1942) proposed an expression of the average degree of consolidation for combined vertical and horizontal drainage U_{vh} as:

$$U = 1 - (1 - U_v)(1 - U_h) \tag{11}$$

The expression of U_{vh} is then obtain by substituting Eq.9 and Eq.10a into Eq.11 which gives:

$$U_{vh} = 1 - \sum_{n=0}^{n=\infty}\frac{2}{M^2}\exp[-M^2 T_v - 2\nu_{hv} T_v] \tag{12}$$

Where: ν_{hv} is the ratio of time factors in horizontal and vertical directions, according to Guo et al. 2018(a,b), It is calculated as:

$$\nu_{hv} = \frac{4}{\mu}\frac{c_h}{c_v}\frac{H^2}{D^2} \tag{13}$$

Solving Eq.12 for different values of ν_{hv} gives the U_{vh} vs T_v curves as shown in Fig.1(a). The case of Terzaghi's one dimensional equation is represented by the curve where $\nu_{hv} = 0$.

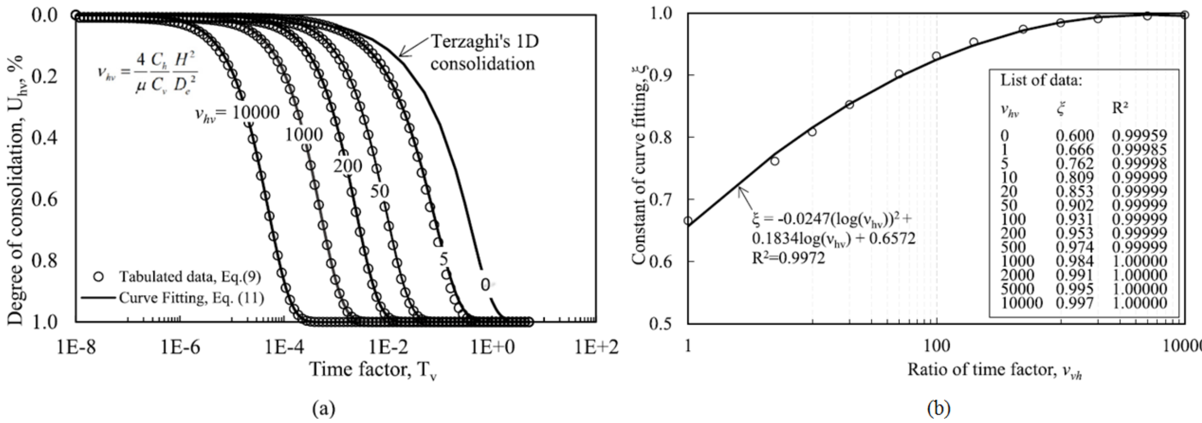

*Fig.1: **a)** Effect of ν_{hv} on the U_{vh} versus T_v curves. **b)** Effect of ν_{hv} on the constants of curve fitting ξ{ Guo et al. 2018(b)}*

In this method, Guo et al. (2017 and 2018(b)) adopted the model Chapman-Richards to fit the $U_{vh} - T_v$ curve. The mathematical expression of Chapman-Richards' model can be written as:

$$y = \eta[1 - \kappa \exp(-\mu t)]^{\lambda} + \varepsilon \tag{14}$$

Where: η is the amplitude of the curve. ε is the offset from zero. κ, μ, and λ are rate constants.

Guo et al. (2017 and 2018(b)) found out that the values of κ, η, and ε are 1.0, 1.0 and 0 respectively. The value of μ is 2. Therefore, when Eq.14 is used to fit Terzaghi's consolidation curve, Eq.14 becomes of the following form:

$$U_{vh} = [1 - \exp(-2(\nu_{hv} + 1)T_v)]^{\xi} \tag{15}$$

Where ξ is a curve fitting constant.

The relationship between the constant ξ and ν_{vh} is illustrated in Fig.1(b) . It should be noted that the case where $\nu_{vh} = 0$ and $\xi = 1$, represent the case of Terzaghi's one dimensional consolidation curve as pointed out by Guo & Chu (2017).

By combining Eq.13 and Eq.15, the relationship between soil settlement and time can be written as:

$$\delta = \delta_{ult}[1 - \exp(-2(\nu_{hv} + 1)T_v)]^{\xi} \tag{16}$$

According to Guo et al. (2018b), Eq.15 was derived using excess pore pression distribution. Thus, the settlement estimations by Eq.16 are more accurate where the degree of consolidation is above 40%.

Eq.16 is then used as an observational model to predict δ_{ult} and c_v using the observed settlement data. Guo & Chu (2017) adopted the same procedure as Asaoka, selecting settlement data $\delta_1, \delta_2, \ldots, \delta_n$ at constant time intervals $\Delta t = t_{n+1} - t_n$, and then expressing the relationship between δ_{n+1} and δ_n.This yields to:

$$\delta_i = \delta_{ult}\left[1 - \exp\left(-2(\nu_{hv} + 1)\frac{c_v}{H^2}t_i\right)\right]^{\xi} \tag{17}$$

$$\delta_{i+1} = \delta_{ult}\left[1 - \exp\left(-2(\nu_{hv} + 1)\frac{c_v}{H^2}t_{i+1}\right)\right]^{\xi} \tag{18}$$

δ_i: settlement at time $t_i = \Delta t.i$ (i is an integer)

After combining Eq.17 and Eq.18 the relationship between δ_{n+1} and δ_n can be expressed as:

$$\delta_{i+1}^{1/\xi} = \alpha + \beta\delta_i^{1/\xi} \tag{19}$$

Where:

$$\alpha = (1-\beta)\rho_{\mathrm{ult}}^{1/\xi} \tag{20}$$

$$\beta = \exp\left(-2(\nu_{\mathrm{hv}}+1)\frac{c_v}{H^2}\Delta t\right) \tag{21}$$

From Eq.19, when the curve of $\delta_{n+1}^{1/\xi}$ vs $\delta_n^{1/\xi}$ is plotted, a straight line is obtained where β is the slope and α is the intercept. Therefore, the final settlement δ_{ult} can be estimated by the following expression:

$$\delta_{ult} = \left(\frac{\alpha}{1-\beta}\right)^{\xi} \tag{22}$$

Furthermore, the coefficient of consolidation in the vertical direction can be estimated by:

$$c_v = -\frac{H^2 \ln\beta}{2\Delta t}\frac{1}{1+\nu_{hv}} \tag{23}$$

And the coefficient of consolidation by:

$$c_h = -\frac{\mu D_e^2 \ln\beta}{8\Delta t}\frac{\nu_{hv}}{1+\nu_{hv}} \tag{24}$$

Eq.19 to Eq.24 can be used as observational model to predict the values of δ_{ult}, c_v, and c_h based on monitored settlement data. The procedure is similar to that used in Asaoka's method, it consists of the following steps:

- Calculate the ratio of time factors in horizontal and vertical directions ν_{hv}, and Identify the value of ξ from Fig.1(b)
- Select settlement data set ($\delta_1, \delta_2, \dots \delta_n$) where δ_n is the settlement at time t_n, in a way that $\Delta t = t_n - t_{n-1}$ is constant
- Plot $\delta_{n+1}^{\frac{1}{\xi}}$ vs $\delta_n^{\frac{1}{\xi}}$ curve and determine the slope β and the intercept α
- Calculate the final settlement δ_{ult}, c_v, and c_h using Eq.22, Eq.23 and Eq.24

Guo & Chu(2017) also adopted the same aspect as Edil et al. (1991), where the number of samples needed to achieve 95% of consolidation j_{95} is used. And proposed N_{90} , which is defined as the number of samples needed to achieve a 90% degree of consolidation, where:

$$\left[1-exp\left(-2(\nu_{hv}+1)\frac{c_v}{H^2}N_{90}\Delta t\right)\right]^{\xi} = 90\% \tag{25}$$

From Eq.11 and Eq.15 the number of sampling points N_{90} is $N_{90} = \frac{\ln\,(1-0.9^{\frac{1}{\xi}})}{\ln\beta}$

Although Guo & Chu (2017) found out that the sampling period doesn't have much of an effect on the prediction, yet the number of sampling points N_{90} should have a value greater than 20, in order to achieve a high value of the coefficient of regression for the least-squares linear regression.

The modified hyperbolic method of Guo et al. (2018(a)) [7]:

This method is based on the hyperbolic method developed by (Sridharan et al., 1987; Tan et al.,1991). In this method a new parameter ν_{hv} was introduced, which is defined as the ratio of time factors in the horizontal and vertical directions. This parameter is used to redefine the relationship between U_{vh} and T_v.

Let's remind that the hyperbolic approach uses the linear settlement segment produced when settlement data between U_{60} and U_{90} are plotted as t/δ vs t, this segment represent the relationship:

$$\frac{t}{\delta} = \alpha t + \beta \tag{26}$$

Where α is the slope, and β is the intercept of the linear segment between U_{60} and U_{90}, t is the consolidation time, and δ is the monitored settlement.
From Eq.26 the final consolidation settlement can be obtained as:

$$\delta_{ult} = \frac{1}{\alpha} \tag{27}$$

Furthermore, when radiating lines are drawn from the origin to U_{60} and U_{90} points, the slopes of these lines are 1/0.6 and 1/0.9 respectively. By plotting these lines, direct identifications of U_{60} and U_{90} are performed. Once δ_{60} and δ_{90} are identified from t/δ vs t plot, the estimation of the final settlement is possible by using the equations:

$$\delta_{ult} = \frac{1}{0.6} * \delta_{60} \tag{28}$$

And

$$\delta_{ult} = \frac{1}{0.9} * \delta_{90} \tag{29}$$

The advantage of the hyperbolic method is that it can be extended to clay deposits treated with vertical drains. According to Tan (1996) in reference to Hansbo (1981), for ideal drains the average degree of consolidation can be described as in Eq12a , Eq12b, and Eq12c.

Tan (1993) used the equation for the average degree of consolidation obtained from Carrillo (1942), which is expressed by Eq.11 above.

Using Terzaghi's solution for U_v , Eq.10a, Eq.10b, Eq.10c, and Eq.11, Tan (1993,1994,1995) used different documented history cases in order to produce theoretical hyperbolic settlement-time curves for any practical vertical drain problem. From these case histories. And thus, Fig.2 was obtained.

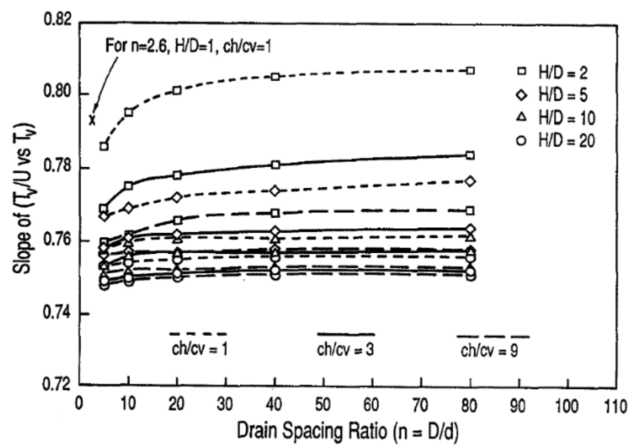

Fig. 2. *Relationship of slopes (α) of initial linear (between U_{60} and U_{90}) segments of theoretical hyperbolic plots with parameters n, H/D and c_h/c_v. {From Tan.1995}*

The slopes α for the first theoretical first linear segment between U_{60} and U_{90} are dependent on soil and drain parameters, the slopes can be obtained from Fig.2 (Tan1995). Therefore, if the initial slopes of segments of the field hyperbolic plots between U_{60} and U_{90} can be determined through observations, then the slopes of radiating lines are given by:

$$S_{60} = \frac{1}{0.6}\frac{S_i}{\lambda} \tag{30}$$

And

$$S_{90} = \frac{1}{0.9}\frac{S_i}{\lambda} \tag{31}$$

λ: the slope of the theoretical segment between U_{60} and U_{90}

S_i: the slope of the experimental segment between δ_{60} and δ_{90}
S_{60} and S_{90} are the slopes of the radiating lines used to identify δ_{60} and δ_{90}

By constructing radiating lines with the slopes described above, δ_{60} and δ_{90} can be located. Hence, the ultimate settlement can be predicted using the equations Eq.28, Eq.29 and the following equation:

$$\delta_{ult} = \frac{\lambda}{S_i} \tag{32}$$

For vertical drainage, the relationship of U_v vs T_v from Terzaghi one dimensional consolidation theory, is given as:

$$U_v = 1 - \sum_{n=0}^{n=\infty} \frac{2}{M^2} exp(-M^2 T_v) \tag{33}$$

The expression of U_{vh} is then obtained as in Eq.12, where:

$$U_{vh} = 1 - \sum_{n=0}^{n=\infty} \frac{2}{M^2} exp[-M^2 T_v - 2\nu_{hv} T_v] \tag{34}$$

Fig.2 shows plots of U_{vh} vs T_v calculated from Eq.34 with $n = 0\ to\ 50$ for different values of ν_{hv}.

Just like in the hyperbolic method, the relationship of $U_{vh} - T_v$ is plotted as T_v/U_{vh} vs T_v, so λ can be identified between U_{60} and U_{90} , and thus λ can be used to predict the final settlement in the hyperbolic method. Values of λ were calculated for different cases of ν_{hv} values, Guo et al. (2018(a)) reported a curve representing the relationship λ vs ν_{hv} illustrated in Fig.3

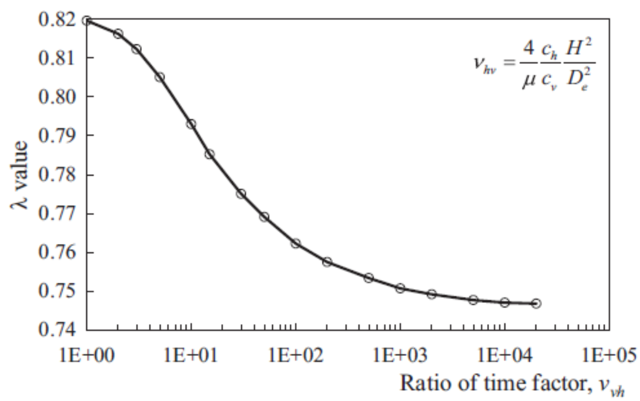

Fig. 3. *Effect of ν_{hv} on λ values.{ from Guo et al. (2018(a)) }*

Fig.3 shows that λ decreases nonlinearly as ν_{hv} increases in the logarithmic scale. By using the curve in Fig.3 λ can be identified and thus the value of the final settlement can be predicted.

Since the procedure of predicting the consolidation settlement by the hyperbolic method is only valid for settlement data between U_{60} and U_{90}. Guo et al. 2018(b) also suggested a new procedure to improve the hyperbolic method. This procedure focus on the identification of the slope of the theoretical curve, it is executed by following the steps below:

1. Calculate the value of ν_{hv} using Eq.13 and proceed to the identification of λ from Fig.3 .
2. Plot the t/δ vs t curve, select a linear segment in the curve, and by a linear regression determine the slope S_i of the linear segment.
3. Substitute the values of λ and S_i in the equations: $S_{60} = \frac{1}{0.6}\frac{S_i}{\lambda}$ and $S_{90} = \frac{1}{0.9}\frac{S_i}{\lambda}$.
4. Draw two lines from the origin with the slopes S_{60} and S_{90} and locate the intersection of these lines with the t/δ vs t curve to obtain the values of t_{60} and t_{90} corresponding to U_{60} and U_{90} respectively.

5. Check if the linear segment selected in step 2 falls in the range between t_{60} and t_{90} from step 4. If there is a disagreement, reselect a linear segment to get a new S_i and repeat steps 2 to 4, until a good agreement between what was selected and the determined intervals is obtained.
6. The slope achieved from the last step is the targeted slope. Calculate ρ_f by substituting the obtained λ and S_i in the Eq.31.

Case study

The three methods discussed above have been processed on a real observational soil settlement data set. The studied soil is under an embankment on the motorway penetrating Bejaia, Algeria.

The studied segment is part of the section 1 (Pk0 to Pk21+400) between the port of Bejaia and the famous Algerian east-west highway . In this particular zone, the Soumam River is limited from the east and the west, respectively, by the national road 75 (RN75), the RN12 and the railway. The route passes close to the industrial facilities of Sonatrach Petroleum Company, Bejaia airport and El Kseur city industrial area. The layout is a 2x3 lane, which runs entirely on embankments.

The section of the motorway follows the Soummam River and passes through swampy agricultural areas requiring, sometimes the use of massive backfill on soft ground. The main problem posed by these embankments is the settlement of the foundation soils. This vertical movement must be known with precision for backfill preparation and implementation. This is why a test embankment was carried out, and instrumented over a period of 360 days; on a marshy area of this section in order to study in situ the real settlement.

The Bejaia motorway test embankment was realized and instrumented for 360 days. The obtained data enabled us to carry out this comparative study in order to better understand the phenomenon of consolidation settlement, in particular, which remains the most difficult to estimate accurately.

The geotechnical in situ survey has been carried out at the Pk13+000. The foundation is mainly composed, top down, of:

- A thin layer of topsoil with a thickness of 0 to 1m.
- A layer of wet and slightly plastic clay with thickness variable from 1 to 3m
- A layer of saturated and poorly plastic clay exceeding 15m of thickness.

It should be noted that the water table is, on average, at 2.16m depth in the study area.

The settlement observations carried on the embankment started on 22/04/2014 and stopped on 17/04/2015 at this point the settlements were already stabilized at 40.64 cm. the settlement observations curve and Soil parameters are illustrated in Fig.5.

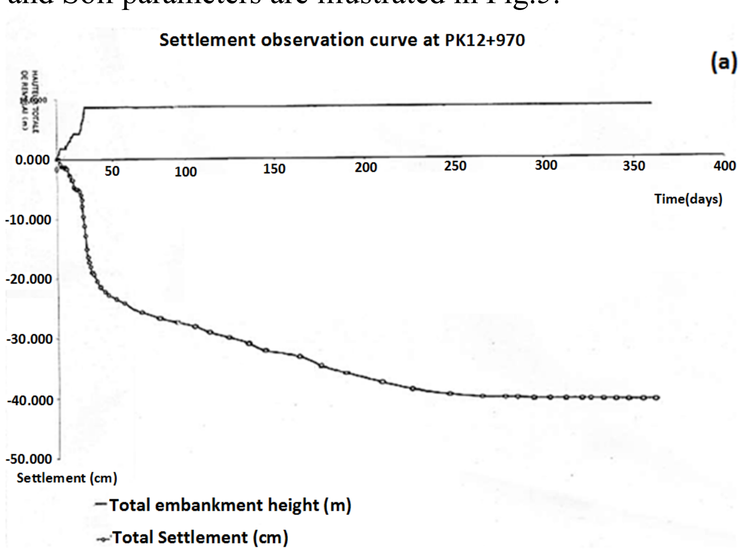

***Fig. 4.** settlement observation curve at PK 12+970 (LCTP, 2013).*

Computation of stress and settlement due to embankment by Terzaghi's method:
According to the theory of Terzaghi, the total or final settlement δ_{ult} of a soil consists of primary settlement δ_p, secondary settlement δ_s and settlement induced by lateral displacements of the considered soil δ_{lat}. Also, the primary settlement has two components: an immediate settlement δ_i and a deferred settlement associated with consolidation δ_c. Hence the overall formula (Costet and Sanglerat, 1981):

$$\delta_{ult} = \delta_p + \delta_s + \delta_{lat} = \delta_i + \delta_c + \delta_s + \delta_{lat} \quad (35)$$

Where: δ_p: primary settlement, δ_s : secondary settlement, δ_{lat}: lateral displacement induced settlement, δ_i : immediate settlement, δ_c: consolidation settlement.

The consolidation settlement is calculated using the expressions from (Costet and Sanglerat, 1981), and the soil stresses are calculated using the expressions from Holtz, et al. (1981).
Taking into account the correction of Skempton and Bjerrum (1957), the calculated values of the components of settlement are: $\delta_c = 40.15cm$, $\delta_i = 12.4cm$, $\delta_s = 7.1cm$, $\delta_{lat} = 3.3cm$
Hence, the final settlement is $\delta_{Terzaghi} = 62.95\ cm$
The degree of consolidation at 360 days can be calculated using the coefficient of consolidation, as (Terzaghi, 1925):$T_v = \frac{3.28*10^{-7}}{\left(\frac{27.8}{2}\right)^2} * 360 * 24 * 3600 = 0.052$
In this case $T_v < 0.5$, hence, according to the approximation of Casagrande: $U = 26\ \%$
The settlement at 360 days, is given by:$\delta_{360} = U \times (S_c) + S_i = 0.26 \times (40.15) + 12.4 = 22.84$ cm

Predicting final settlement by the procedure of Guo et al. (2017&2018(b))
For this procedure, consecutive settlement should be considered. For this case, successive settlement measurements were taken every day, so $\Delta t = 1\ day$, therefore, Fig.5 is obtained, and then used to predict the final settlement.

For this case, no drains were installed in the field, Therefore, this is a Terzaghi one dimensional consolidation case. So, the values of ν_{vh} and ξ are ($\nu_{vh} = 0$, and $= 0.6$). Hence, for the observation procedure, Eq.17 is used to obtain Fig.5.

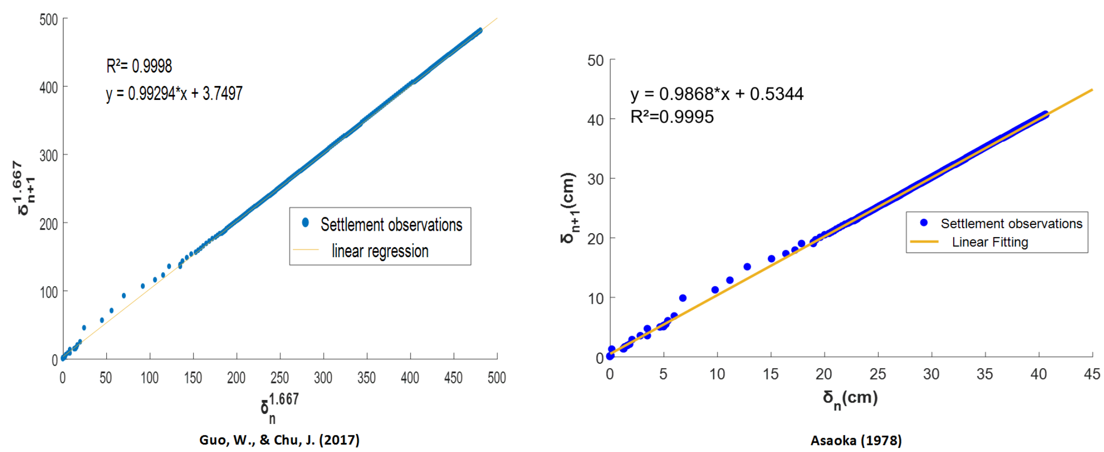

Fig. 5. *Regression curve (using MATLAB) obtained by the application of the method of Guo & Chu (2017) and Asaoka(1978) {data up to 100% were used}*

From Fig. 5, and by a graphical identification, the line formed by settlement data for the method Guo & Chu (2017), has the following equation:

$$\delta_{n+1}^{1.667} = 0.99294\ \delta_n^{1.667} + 3.7497 \quad (36)$$

Where the slope β=0.99294, and the intercept $\alpha = 3.7497$.
the line formed by settlement data for Asaoka's method the line formed by settlement data for:

$$\delta_n = 0.9868\ \delta_{n-1} + 0.5344 \tag{37}$$

Where: $\beta_1 = 0.9868\ and\ \beta_0 = 0.5344$

From Eq.36 the predicted final settlement is 43.16 cm. comparing it to the measured settlement at 360 days indicates an over estimation of 6%.

The error was calculated as follows: $Error\% = \left(\frac{\delta_e - \delta_{real}}{\delta_{real}}\right) \times 100;\ \delta_e: estimated\ settlement.$

The number of sampling point N_{90} is greater than 20 which means that the condition for this procedure to achieve a higher accuracy is respected.

On the other hand, the prediction using Asaoka's method yielded a value of 40.48 cm. when compared with the measured settlement value at 360 days, the predicted value has an error of 0.4%.

Predicting settlement by the procedure of Guo et al. 2018(a)

In this method, Settlement data are plotted as the t/δ vs t. The procedure concentrates on the linear part of the obtained curve, which has the form of Eq.26.

The obtained curve and the selected linear segment are illustrated in Fig.6 **(a)**. The segment has the following expression: $Y = 0.02489\ x + 0.8448$.

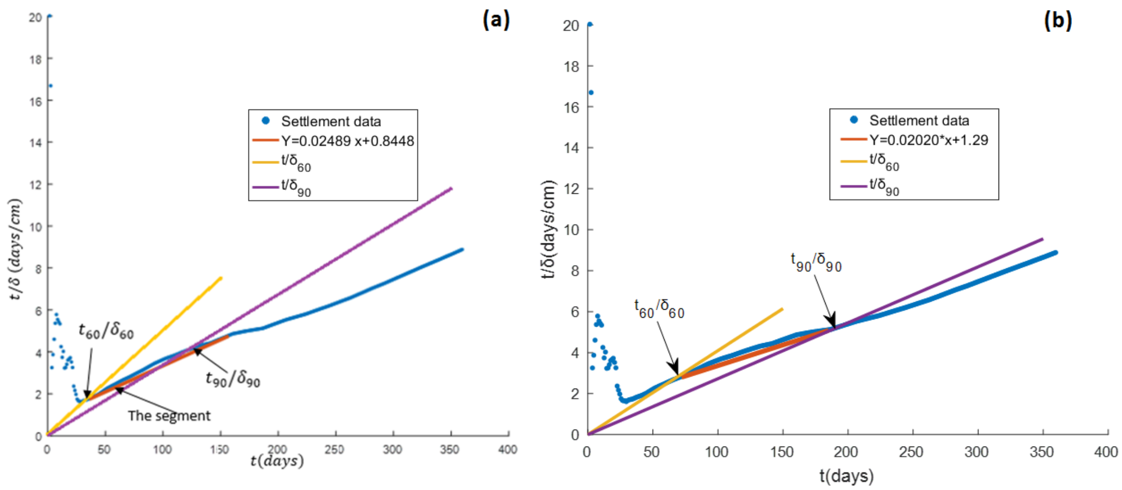

Fig. 6. *curve of the suggested procedure for the hyperbolic method (Guo et al. 2018) used to predict the final settlement **(a)** first attempt **(b)** final phase*

In this case of embankments, no vertical drains were installed. So, the slope λ of the theoretical curve would be equal to that of the case of the one-dimensional consolidation of Terzaghi which is according to Guo et al. 2018(a) equal to 0.82. having the value of λ will allow us to construct the lines needed to locate δ_{60} and δ_{90}. And thus Fig.6 (a) is obtained, where it's clear that the segment doesn't fall in the range of δ_{60} and δ_{90} which requires a reselection of the segment as suggested in the procedure of the method.

After few attempts of the reselection of the segment a successful attempt curve is obtained (Shown in Fig.6**(b)**), in which the selected segment has a slope equal to 0.02020, it is located between U_{60} and U_{90}, where the lines constructed to locate δ_{60} and δ_{90} have the slopes $S_{60} = 0.0410$ and $S_{90} = 0.0273$. Hence, the final settlement can be predicted using either Eq.30, Eq.31, or Eq.32. So:

$$\delta_{ult} = \frac{\lambda}{S_i} = \frac{0.82}{0.0202} = 40.59cm \tag{38}$$

Results and discussions

Table 1 shows the comparison results between the methods processed above. It shows the predicted final settlement with the associated error compared to field value. Also, the intermediate settlement at (360 days) estimates for each method are given.

Table 1: *results of the prediction of the final settlement and estimation of settlement after 360 days by the methods of (Terzaghi (1948), Asaoka (1978), Guo, & Chu (2017,2018b), Guo et al. (2018a)*

Methods	**Terzaghi (1948)**	**Asaoka (1978)**	**Guo et al. [5]&[6]**	**Guo et al. [7]**	**Field final settlement δ_{ult}**
Predicted δ_{ult} (cm)	62.95	40.48	43.16	40.59	40.64
Error % $\left\lvert\frac{\delta_{estimated}-\delta_{real}}{\delta_{real}}\right\rvert \times 100$	54.89%	0.4%	6.2%	0.1%	-
Settlement at 360 days (estimated) cm	22.84	40.12	41.10	34.47	-
Measured settlement at 360 days	40.64 cm				

For the estimation of the settlement at 360 days Eq. 37 was used for Asaoka's method by considering the settlement at 10 days as a starting point, Eq.16 for Guo et al (2017,2018b), and for Guo et al. 2018 (a) the following expression was used:

$$\delta(t) = \frac{\lambda \times t}{\alpha \times t + \beta} \tag{39}$$

From Table 1, it can be noted that the observational methods (Asaoka (1978), Guo et al. (2017,2018b), Guo et al. (2018a) show better accuracy in predicting the final settlement than Terzaghi's method which has an error of 54.89%.

As for the observational methods, it can be noted that their errors associated with these methods are comparable, although Guo et al. 2018a is better.

Now, concerning the observational methods' results, it can be concluded that the methods of Asaoka (1978) and Guo et al. (2017,2018b) seems to be better than the method of Guo et al. 2018 (a), due to the fact that the first two methods are less demanding in terms of observational data. Indeed, these approaches are functional even if fewer measurements of settlement are available, meanwhile Guo et al. 2018a requires at least settlement observations beyond 60% of consolidation.

On the other hand, for the intermediate settlement at 360 days, the estimation by Terzaghi's method yielded value that is equivalent to 56% of the actual measured value. For the method of Guo et al. 2018 (a) it yielded a value of 34.5 cm which represents 85% of the actual settlement although the predicted final settlement is the most accurate. As for Asaoka (1978), and Guo et al. (2017,2018b) the estimated settlements at 360 days are reasonably accurate, which confirms the previous conclusion.

Conclusion

In this paper, two recent and promising methods for final soil settlement prediction were tested on a real settlement data set, and compared with the prediction by Terzaghi's, and Asaoka's method. At first, it was clear that the methods based on field data have better accuracy than those based on laboratory test in term of predicting the final soil settlement. It is also noticed that the prediction error for the final settlement by Guo et al. (2018a) method was far smaller than Guo et al. (2017, 2018b). Furthermore, for the intermediate settlement at 360 days the estimations showed that Guo et al. (2018a) yielded an underestimation, unlike the method of Guo et al. (2017, 2018b) which is found to be more accurate.

It can be concluded that the method of Guo et al. (2017, 2018b) is preferred for the estimation of intermediate settlements, whereas, Guo et al. (2018a) is preferable for the prediction of final settlements, despite its complicated procedure.

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