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Study on the hydraulic conductivity of Boom clay

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Abstract

The hydraulic conductivity is a key parameter in geotechnical engineering practice for the seepage and consolidation analysis. Experimental results show that the hydraulic conductivity is mainly governed by the soil porosity, and the correlations with void ratio are usually proposed. The validity of these correlations has been verified for soft clays and sands. However, few studies were involved in stiff clays. In this work, the hydraulic conductivity of Boom clay, a stiff clay taken from the Essen site in Belgium, was determined from both consolidation and constant-head percolation tests. The data obtained was then analyzed to evaluate the existing correlations to predict the hydraulic conductivity. In addition, as these correlations usually require a referred hydraulic conductivity at a known void ratio, it is often difficult to be used in practice. Thus, a new method was developed allowing the prediction of hydraulic conductivity without the referred value, which was based on two existing correlations and involved the void ratio and the liquid limit. The proposed correlation was verified using the experimental results obtained from Boom clay samples which were collected from various locations in Belgium.

Keywords: Boom clay; consolidation; constant-head percolation; hydraulic conductivity; void ratio; correlation.


1 Introduction

Boom clay is a thick deposit of over-consolidated marine clay, of Oligocene age. It can be found in the north-east region of Belgium (Bouazza et al. 1996). Its hydraulic conductivity has been investigated for its performance assessment for the deep geological disposal of high-level radioactive waste. Recently, Wemaere et al. (2008) has worked on Boom clay cores taken from four distant boreholes at various depths. The results showed a variability of hydraulic conductivity ranging from $3 \times 10^{-12}$ to $10 \times 10^{-12}$ m/s.

In the laboratory, hydraulic conductivity is usually determined using Darcy’s law. The constant-head method is usually applied for high permeability soils (sandy soils for example) and the variable-head method is usually used for low permeability soils (clayey soils for example). For stiff clays or rocks with extremely low hydraulic conductivity (sometimes lower than $10^{-12}$ m/s), pulse tests are usually used (Zhang et al., 2000). In addition to these direct methods, Terzaghi’s consolidation theory can also be used to determine the hydraulic conductivity by back analyzing the consolidation results (Delage et al., 2000).

Experimental results usually show that hydraulic conductivity ($k$) mainly depends on soil porosity and various correlations are proposed between hydraulic conductivity ($k$) and void ratio ($e$). Some of these correlations are presented in Table 1. The correlation by Taylor (1948) (equation No. 1) was modified by Samarasinghe et al. (1982) for sandy soils where $C$ and $m$ are two constants (after Indraratna and Rujikiatkamjorn, 2004). Aubertin et al. (1996) and Sridharan and Nagaraj (2005) analyzed the effects of $m$ and proposed $m = 5$ for clays. Kozeny (1927) and Carman (1938, 1956) proposed another correlation (i.e. KC function) for porous materials between void ratio and hydraulic conductivity as equation No. 2, where $\gamma$ is the unit weight of the fluid involved; $\mu$ is the viscosity of the fluid, $C_{K-C}$ is the Kozeny-Carman empirical coefficient and $S_o$ is the specific surface area per unit volume of particles (after David, 2003). Note that if the value of $m$ in equation No. 1 is set as 3, the relation between hydraulic conductivity and void ratio is the same as $k \propto e^3/(1+e)$. Aubertin et al. (1996), Sridharan and Nagaraj (2005) found that the value of $m$ is generally close to 5 for clays; hence, KC function would over-evaluate the hydraulic conductivity when the void ratio is less than 1.0.

For clayey soils, Taylor (1948) also proposed equation No. 3 where $C_k$ is a permeability change index, $k_o$ and $e_o$ are referred values (usually, the in-situ values) of hydraulic conductivity and void ratio respectively (after Indraratna and Rujikiatkamjorn, 2004). Tavenas et al. (1983) and Leroueil et al. (1990a, 1990b) applied equation No. 3 to soft
clays with a wide range of void ratios, and proposed that $C_k$ is a function of the in-situ void ratio $e_0$: $C_k = 0.5e_0$. Mesri et al. (1994) analyzed the data of soft clays and proposed equation No. 4 where $CF$ is clay fraction and $A_c$ is soil activity. Although there are various correlations proposed, equation No. 3 is usually used to describe the variation of hydraulic conductivity of clays versus void ratio changes. Note that these equations have been only validated for soft clays whose in-situ void ratio ($e_0$) is larger than 1.0. The validation of these equations for stiff clays with a void ratio often lower than 1.0, remains to be verified.

In the present work, the hydraulic conductivity of Boom clay cores of low in-situ void ratio ($e_0 < 0.79$) taken from a borehole drilled in Essen (Belgium) was determined from oedometer and isotropic consolidation tests as well as constant-head percolation tests. Four depths in the range of 220 – 250 m were investigated. The obtained results were used to evaluate the existing correlations listed in Table 1. A new method was developed allowing prediction of the hydraulic conductivity of stiff clays using the void ratio and the liquid limit. This method was verified using the experimental results from Boom clay samples taken from various locations.

2 Soils studied

The soil cores studied were taken from the borehole drilled in Essen (Belgium). The Essen site situates in the north east of Belgium, 60 km far from the underground research laboratory (URL) at the Mol site (Figure 1). The Boom clay formation ranged from 153 to 280-m in depth. It can be sub-divided into four zones: Transition zone (153 – 200 m); Putte member (200 – 238 m); Terhagen Member (238 – 260 m); and Belsele-Waas Member (260 – 280 m).

Four cores with 1 m in length and 100 mm in diameter were studied. After being taken from the borehole, the cores were sealed in plastic tubes with ends closed and transported to the laboratory for testing. The details of these cores are shown in Table 2. Two cores were taken from the Putte member (Ess75 and Ess83) and two others from the Terhagen members (Ess96 and Ess104). The geotechnical identification parameters of these cores are similar: specific gravity, $G_s = 2.64 – 2.68$; liquid limit, $w_L = 68 – 78\%$; plastic limit, $w_P = 29 – 33\%$; plastic index, $I_P = 36 – 45$. The water content ($w$) ranges between 26.5 and 29.7 \%, and the void ratio ($e$) between 0.700 and 0.785. The values of degree of saturation ($S_r$) determined in the laboratory on the cores are equal or close to 100\%. The Blue Methylene value (VBS) is equally similar, VBS = 6.20 – 6.67. According to the relationship between the specific surface area (SSA) and VBS (Yukselen and Kaya, 2008), the SSA of Boom clay ranges from 152 to 163 m$^2$/g. Nevertheless, the carbonate content of core Ess104 (43.6 g/kg) is significantly higher than that of other cores (lower than 10 g/kg). The particle size distribution determined is shown in Figure 2. The curves obtained for the four depths are similar and the clay content ($< 2 \mu$m) is quite high (more than 40\%). Note that the particle size distribution of Boom clay
at Essen is very similar to that presented by Wemaere et al. (2008) for Boom clay taken from other regions in Belgium (Mol, Doel, Zoersel and Weelde).

3 Experimental techniques

Three methods were used to study the hydraulic conductivity of the soil cores: (1) constant-head method using an oedometer cell; (2) back-analysis of consolidation tests in an oedometer cell; (3) Back-analysis of consolidation tests in an isotropic cell. A synthetic solution having a similar chemical composition as the in-situ pore-water was used to perform the tests. In Table 3, the composition of salts used for preparing the synthetic solution is presented for all depths. A high concentration of NaCl (15 – 20 g/L) can be observed. More details on the pore-water chemistry of Boom clay at Essen can be found in De Craen et al. (2006).

For the tests in the oedometer cell, a 40 mm long section was cut from the soil core using a metal saw. The confining ring of the oedometer cell having a sharp edge was then pushed into the soil sample. The surfaces of the soil specimen were finished using a steel knife with sharp edge. The final dimension of the soil specimen is 20 mm high and 50 mm in diameter. Note that special attention was paid to sampling direction: the axis of specimens is perpendicular to the bedding plan. The confining ring having the soil specimen inside was then installed in the oedometer cell. For tests using the isotropic cell, the soil specimen was carefully hand-trimmed to have a final dimension of 38 mm in diameter and 76 mm high. The axis of the specimen is also perpendicular to the bedding plane.

When applying the constant-head test in the oedometer cell, a vertical stress equal to the in-situ vertical stress estimated from the soil densities and depths was applied after installation of the soil specimen in the cell. The specimen was fully saturated and this was checked by considering the initial degree of saturation (see Table 2) and the volume changes due to the in-situ stress application. After stabilization of the soil deformation under this initial load, the porous stone in the base of the cell was fully saturated by the synthetic solution flushing. It was observed that this operation did not induce any volume change of the soil. A water pressure of 1.0 MPa was then applied using a controller of pressure/volume (CPV) from the lower base of the cell; the upper base was kept at atmospheric pressure. The hydraulic conductivity of the soil was calculated from the water volume change recorded by the CPV with Darcy’s law. Two tests were performed using this method on core Ess83 (227 m depth) and Ess96 (239 m depth). The in-situ vertical stress was estimated to be 2.27 MPa, based on a mean value of the unit weight estimated at 20 kN/m$^3$ and a ground water level considered at the ground surface. In the oedometer test, a value of 2.40 MPa was chosen to represent the in-situ vertical stress.

To apply the second method, one oedometer consolidation test was carried out on each of the four cores of Table 2. A vertical stress equal to the in-situ stress was applied to the specimen after its installation inside the cell. After stabilization of the volume change, the subsequent saturation of the drainage system was performed without inducing any volume
change of soil. The soil was then subjected to several unloading/loading paths in steps with vertical stresses ranging from 0.05 to 32 MPa. The hydraulic conductivity was finally determined following the Casagrande’s method (AFNOR, 2005a).

To apply the third method, one isotropic consolidation test was carried out on each of the four cores of Table 2. The high-pressure isotropic cell described by Cui et al. (2009) was used for this purpose. After installation of the soil sample on the pedestal with dry porous stones, a confining pressure equal to the in-situ stress was applied. After stabilization of the soil volume change, the drainage system was fully saturated by the synthetic solution. As in the case of oedometer tests, no volume change was observed during this operation. Later, the confining pressure and the back pressure were then increased at the same time by a same pressure increment. The final back pressure was equal to 1.0 MPa and the effective pressure of the soil was still equal to the in situ stress. After Delage et al. (2007), this procedure allows a satisfactory saturation of the soil sample without disturbing its initial state (in terms of microstructure and stress state). Finally, the confining pressure was incrementally increased, allowing the determination of the hydraulic conductivity at various void ratios following Casagrande’s method (AFNOR, 2005a).

4 Experimental results

In Figure 3, the results obtained from the test using the constant-head method are shown. The volume of solution passing through the soil specimen (20 mm high) under a pressure gradient of 1.0 MPa is plotted versus time. For Ess83, a seepage velocity of \(1.23 \times 10^{-8}\) m/s can be determined and the hydraulic gradient \(i\) being 5000 (water head divided by sample height), hence the hydraulic conductivity \(k\) is \(2.46 \times 10^{-12}\) m/s (at a void ratio of 0.640); For Ess96, the seepage velocity is \(1.00 \times 10^{-8}\) m/s and the hydraulic conductivity \(k\) is \(2.00 \times 10^{-12}\) m/s (at a void ratio of 0.586. Note that during this step, no obvious vertical deformation was observed for both samples.

Using the results from the oedometer test on Ess83, the relationship between the calculated void ratio and the corresponding vertical stress can be obtained as shown in Error! Source du renvoi introuvable. The initial loading to the in-situ stress decreased the void ratio from 0.730 to 0.651 (point A). The saturation of the drainage system did not induce significant change in void ratio. The subsequent unloading in steps to 0.125 MPa increased the void ratio up to 0.774 (point B). After the loading in steps to 16 MPa, the void ratio decreased to 0.361 (point C). For the subsequent paths, the void ratios were equal to 0.620 for \(\sigma_v = 0.125\) MPa (point D), 0.270 for \(\sigma_v = 30\) MPa (point E), and 0.569 for \(\sigma_v = 0.125\) MPa (point F). Note that the volume change was considered as stabilized when the deformation
rate was less than 0.00125 mm/h following the French standard (AFNOR, 1995). It can be
observed that the time needed for the stabilization during the unloading steps was generally
longer than during the loading steps. A total of about 80 days was needed to finish the
oedometer test.

The hydraulic conductivity using the second method (back analysis from consolidation
tests using the oedometer cell) is presented in Figure 5 versus the corresponding void ratio. It
can be observed that the relationship between void ratio and hydraulic conductivity can be
described with a linear correlation in the semi-logarithmic coordinate. Furthermore, this
relationship seems to be independent of the loading history; a unique function can be
proposed for all the loading and unloading steps as \( k = 0.015 \times 10^{3.1r} (10^{-12} \text{ m/s}) \).

The results of the isotropic consolidation test on Ess83 are also shown in Figure 4, in
terms of variations of void ratio as a function of effective pressure. It can be observed that
from the in-situ stress of 2.40 MPa (initial void ratio of 0.725), loading in steps up to 20 MPa
effective pressure decreased the void ratio to 0.426. Moreover, the relationship between void
ratio and the logarithm of \((p-p_u)\) can be described with a linear correlation. This corresponds
to the compression curve of a normally consolidated soil with a compression index \(C_c\) equal
to 0.31. It should be noted that in this test each loading step was maintained until stabilization
of the volumetric strain according to the French standard (AFNOR, 2005b): the volumetric
strain rate should be less than \(6 \times 10^{-5}/h\). The time needed for each step varied from 100 h to
250 h. A total of 40 days was needed to finish the test.

The hydraulic conductivity using the third method (back analysis from the consolidation
tests using the high-pressure isotropic cell) was also presented in Figure 5, versus void ratio.
As observed in the case of the consolidation test in the oedometer cell, a linear function can
be proposed to correlate the relationship between void ratio and the logarithm of hydraulic
conductivity: \( k = 0.09 \times 10^{4.1r} (10^{-12} \text{ m/s}) \). This expression is similar to that obtained from the
oedometer test.

In order to evaluate the three methods used for the hydraulic conductivity determination,
the result of Ess83 obtained by the first method is also presented in Figure 5. It can be
observed that similar results were obtained by the three methods: the hydraulic conductivity at
a void ratio of 0.64 is between \(1.5 \times 10^{-12} \text{ m/s}\) and \(5 \times 10^{-12} \text{ m/s}\), with a value of \(2.5 \times 10^{-12} \text{ m/s}\)
obtained by the constant-head method. Note that for Ess96 the three methods gave also
similar results: the hydraulic conductivity at a void ratio of 0.59 is between \(0.9 \times 10^{-12} \text{ m/s}\) and
\(2.1 \times 10^{-12} \text{ m/s}\), with a value of \(2.0 \times 10^{-12} \text{ m/s}\) obtained by the constant-head method. The
difference between the results by the three methods is due to both the experimental error and
the heterogeneity of natural Boom clay.

All the results obtained from Ess83 core are gathered in Figure 6b. As mentioned before, for
Ess96, all the three methods (constant-head method, consolidation using the oedometer and
the isotropic cell, respectively) were applied. Only the second and third methods were applied
for Ess75 Ess104. The results are plotted in Figure 6c for Ess96, in Figure 6a for Ess75 and in
Figure 6d for Ess104. It can be observed that, on the whole, the relationship between void
ratio and the logarithm of hydraulic conductivity can be satisfactorily correlated with a linear
function. Furthermore, the functions obtained for Ess75, Ess83, Ess96 and Ess104 are similar
(see Table 4 for all fitting equations).

5 Prediction of hydraulic conductivity

The existing correlations allowing the prediction of hydraulic conductivity (in Table 1)
can be generally rewritten as \( k = C f(e) \), where \( C \) is a parameter. In some cases, \( C \) can be
correlated with the initial void ratio \( e_0 \), and the corresponding hydraulic conductivity \( k_0 \),
such as equation No. 1 and No. 3 in Table 1. In other cases, \( C \) is correlated with other soil
basic parameters (equation No. 2 and No. 4). In equation No. 1, \( m \) is a parameter related to the
curve shape. As mentioned before, the results of Aubertin et al. (1996) and Sridharan and
Nagaraj (2005) showed that \( m \) is equal to 5 for clays.

In the following sections, the experimental data obtained on Boom clay from Essen and
that from Mol (Delage et al., 2000; Aertsens et al., 2004; Coll, 2005; Le, 2008; Wemaere et al.
2008) are used to assess the various models presented in Table 1. The models requiring the
initial hydraulic conductivity \( (k_0) \) and the initial void ratio \( (e_0) \) are firstly evaluated. The two
models that do not require \( k_0 \) and \( e_0 \) are considered afterwards. Finally, a new correlation
is proposed for Boom clay.

5.1 Evaluation of existing models requiring \( k_0 \) and \( e_0 \)

To further evaluate the correlation between hydraulic conductivity and void ratio, \( f(e) \),
the equations of other forms in Table 1 are transformed to \( k = C \frac{e^3}{1+e} \) (from equation No. 2)
and \( k = C e^4 \) (from equation No. 4), where \( C \) can be calculated using \( k_0 \) and \( e_0 \) as
\[
C = \frac{k_0}{f(e_0)}.
\]

In order to evaluate the predicting models, the two following parameters were calculated:
(1) $a$ is the mean value of $R$ ($a = \frac{1}{N} \sum_{i=1}^{N} R_i$); (2) $b$ is the root mean square error of $R$ 

$$
(b = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (R_i - 1)^2}); \text{ where } R \text{ is defined as the ratio of the predicted value } k_{\text{predicted}} \text{ to the calculated experiment value } k_{\text{calculated}} \text{ and } N \text{ is the statistical number (Tang et al. 2008).}
$$

In Figure 7, the hydraulic conductivity values predicted by the above equations are plotted versus the calculated values for the four soil cores from Essen ($a$, $b$, $c$, $d$) and Boom clay from Mol ($e$). In Figure 7f, all the data are put together for the analysis. The mean value of $R$ and the root mean square error of $R$ are shown in Table 5.

It can be observed that equation No. 1 underestimates the hydraulic conductivity for almost all cores (except Ess83) with a relative large scatter ($b = 0.5$). On the contrary, equation No. 2 overestimates the hydraulic conductivity for all cores with a large scatter ($b = 0.8$). Equation No. 3 and No. 4 can predict the hydraulic conductivity satisfactorily for all cores.

As a conclusion, when $k_0$ and $e_0$ are available, equation No. 3 and No. 4 are suitable for predicting the hydraulic conductivity of Boom clay by modifying these equations as

$$
k = k_0 \times 10^{0.56e_0} \text{ and } k = \frac{k_0}{e_0} e^4, \text{ respectively.}
$$

5.2 Models without $k_0$ and $e_0$  

For Boom clay in particular or stiff clays in general, the hydraulic conductivity is low and thus difficult to be determined. Hence, from a practical point of view, it is essential to predict the hydraulic conductivity without measuring $k_0$. For this purpose, equation No. 2 can be developed as follows (after David, 2003; at a temperature of 20 °C):

$$
k = Cf(e) = \frac{\gamma}{\mu C_{k-C}} \frac{1}{S_0^2} \frac{e^3}{1+e} = \frac{20000}{S_0^2} \frac{e^3}{1+e} (m/s)
$$

where $S_0$ is the specific surface area.

The correlation by Mbonimpa et al. (2002) was applied to estimate $S_0$ from the liquid
limit \( w_L \) of Boom clay: 
\[
S_0 = \frac{2.0 \times 10^5}{\gamma_s} w_L^{1.45} (m^2 / m^3).
\]

While the data of the specific surface area \( S_0 \) of Boom clay calculated using VBS (in Table 2) according to Yukselen and Kaya (2008) and liquid limit \( w_L \) were used to verify the correlation by Mbonimpa et al. (2002). With this correlation, the hydraulic conductivity expression can be rewritten as

\[
k = \frac{5.0 \times 10^{-5}}{\gamma_s w_L^{2.9}} e^3 \left(1 + e\right) \quad (m/s)
\]

where \( \gamma_s \) is the unit weight of soil particles.

The above expression [2] and equation No. 4 (in Table 1) were used to predict the hydraulic conductivity of Boom clay from Essen and Mol without using \( k_0 \). The predicted values are plotted versus the calculated (or measured) values in Figure 8a (equation No. 2) and Figure 8b (equation No. 4). The parameters \( a \) and \( b \) are also presented to evaluate these models.

From Figure 8a, it can be observed that the mean value \( a \left( k_{\text{predicted}} / k_{\text{calculated}} \right) \) ranges from 1.9 to 2.8 and the error \( b \) ranges from 1.1 to 2.2. When the void ratio is close to the in-situ value, the predicted hydraulic conductivity fits well with the calculated one; but if the soils are compressed and the void ratio is decreased, the hydraulic conductivity will be over-evaluated. For equation No. 4 (Figure 8b), the mean value \( a \) ranges from 5.6 to 11.2 and the error \( b \) ranges from 5.2 to 11.1. That means this equation overestimates by about 10 times the hydraulic conductivity of Boom clay.

As a conclusion, when the measurement of \( k_0 \) is not available, equation No. 2 can be used by combining the correlation between \( S_0 \) and \( w_L \) (Mbonimpa et al., 2002). A satisfactory agreement between prediction and calculation can be obtained, especially when the void ratio is close to the in-situ value.

**5.3 A correlation for Boom clay**

The above evaluation shows that equation No. 3 in Table 1 is suitable for describing the relationship between \( k \) and \( e \) and has been used in various works (Leroueil et al., 1990a, 1990b; Nagaraj and Miura, 2001), while equation No. 2 presents the advantage of estimating parameter \( C \) without measuring \( k_0 \). As \( C_{K-C} \) in equation No. 2 is a function of \( w_L^{2.9} \), the following equation can be then proposed:

\[
k = \frac{A}{w_L^{2.9}} \times 10^{Be} (m/s)
\]
Where $A$ and $B$ are two constants. In the case of Boom clay, the back analysis gives:

$$A = 3.2 \times 10^{-9} \text{ (m/s)} \text{ and } B = 3.56.$$  

In Figure 9, the hydraulic conductivity calculated from the proposed correlation is presented versus the measured values. As the parameters were fitted using the data by back analysis, the value of $a$ is equal to 1.0; the error $b$ obtained is equally small, $b = 0.4$. Note that there are more data available for higher hydraulic conductivity than for lower conductivity, and therefore the proposed correlation is more suitable for the range of high hydraulic conductivity.

With the proposed correlation and the values of $w_L (59\% - 83\%)$ and $e_0 (0.56 - 0.68)$ reported by François et al. (2009), the predicted hydraulic conductivity using expression [3] $(0.9 \times 10^{-12} - 4.4 \times 10^{-12} \text{ m/s})$ covers the range of the hydraulic conductivity of Boom clay $(1.2 \times 10^{-12} - 4.2 \times 10^{-12} \text{ m/s})$ measured by Aertsen et al. (2004) at Mol and by Wemaere et al. (2008) at Mol, Doel, Zoerel and Weedle.

**6 Discussion**

From the correlation between hydraulic conductivity and void ratio in Figure 6, it can be seen that all the correlations in the coordinate $\log k - e$ show a linear relationship. Hence, equation No. 3 is suitable for Boom clay. The $C_k$ parameter ($C_k = \Delta e / \Delta \log k$) of Boom clay at Essen and Mol (collected from the present work and others) and Singapore clay (after Arulrajah and Bo, 2008) are calculated and plotted in Figure 10, versus $e_0$. According to the analysis on the data presented by Tavenas et al. (1983), the correlation $C_k = 0.5e_0$ is also plotted. The results of Singapore clay are plotted for its low value of $e_0 (< 1.0)$, comparable with the initial void ratio of Boom clay. Figure 10 shows that the values of $C_k$ for Boom clay and Singapore clay lie generally below the line of $C_k = 0.5e_0$. Moreover, $C_k$ of Boom clay is not correlated with $e_0$.

In this study, the correlation $k = \frac{A}{w_L^{\gamma_k}} \times 10^{6\gamma_k} (m/s)$ has been proposed for Boom clay with $A = 3.2 \times 10^{-9}$ and $B = 3.56$. Actually, from equation No. 3 (Table 1), if $C_k$ is taken as the mean value of $C_k$ for Boom clay ($C_k = 0.3$), the $B$ value is equal to 3.33. This value is similar to that obtained for the proposed correlation. On the other hand, the value of $A$ can be also calculated from equation No. 2. Indeed, taking the unit weight $\gamma_k$ of Boom clay equal to
2.68 kN/m$^3$, this equation ($k = \frac{5.0 \times 10^{-7} \gamma_L^2}{w_L^{2.9}} e^3 \frac{e}{1+e}$) allows parameter $A$ to be deduced: $A = 7.0 \times 10^{-6}$. This value is 2200 times larger than that obtained from the correlation [3]. However, when the void ratio is equal to 0.77, the predicted hydraulic conductivity by both equation No. 2 and correlation [3] is close to the measured one.

7 Conclusions

There have been various works in the literatures focusing on the measurement and the prediction of hydraulic conductivity of soft clays. Satisfactory agreement is often obtained. For stiff clays as Boom clay, the existing correlations are however not verified. In the present work, the hydraulic conductivity of Boom clay taken from the Essen site in Belgium was first measured using various techniques (constant-head method or back-analysis from consolidation tests). The results show a strong correlation between the hydraulic conductivity and the void ratio. Secondly, the obtained results and the results collected from other works on Boom clay were used to evaluate some existing correlations. The following conclusions can be drawn:

(1) When the in-situ hydraulic conductivity $k_0$ and the in situ void ratio $e_0$ are available, the two following equations can give satisfactory predictions:

$$k = k_0 \times 10^{0.5e}$$

$$k = \frac{k_0}{e_0} e^4$$

(2) When the in-situ hydraulic conductivity is not available, the following equation can be used for stiff clay especially when the void ratio is close to the in-situ value:

$$k = \frac{5.0 \times 10^{-5} \gamma_L^2}{w_L^{2.9}} e^3 \frac{e}{1+e}$$

This equation was verified using the experimental data on Boom clay.

(3) In the case of Boom clay, the following equation was proposed:

$$k = \frac{3.2 \times 10^{-6}}{w_L^{2.9}} 10^{3.56e}$$

This equation was developed based on the linear correlation observed on the experimental data between the logarithm of hydraulic conductivity and void ratio. The liquid limit $w_L$ is introduced to take into account the variable characterization of Boom clay at various locations.
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17 Figure 8. Predicted hydraulic conductivity versus experimental one – models without $k_0$; (a) Equation
18 No. 2, (b) Equation No. 4
19 Figure 9. Hydraulic conductivity predicted by the proposed correlation versus the experimental one
20 Figure 10. Relationship between $C_k$ and initial void ratio $e_0$
### Table 1. Correlations between hydraulic conductivity and void ratio

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Proponent</th>
<th>Correlations</th>
<th>Soil type</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Taylor (1948)</td>
<td>$k = C \frac{e^m}{1+e}$</td>
<td>Sand and clay</td>
<td>Indraratna and Rujikiatkamjorn (2004)</td>
</tr>
<tr>
<td>2</td>
<td>Kozeny (1927) and Carman (1938, 1956)</td>
<td>$k = \frac{\gamma}{\mu C_{k-e} S_0^2} \frac{e^0}{1+e}$</td>
<td>Porous materials</td>
<td>David (2003)</td>
</tr>
<tr>
<td>3</td>
<td>Taylor (1948)</td>
<td>$k = k_0 \times 10^{\frac{e}{c_i}}$</td>
<td>Soft Clay</td>
<td>Indraratna and Rujikiatkamjorn (2004)</td>
</tr>
<tr>
<td>4</td>
<td>Mesri et al. (1994)</td>
<td>$k = 6.54 \times 10^{-11} \left( \frac{e / CF}{A_e + 1} \right)^4$</td>
<td>Soft Clay</td>
<td>Mesri et al. (1994)</td>
</tr>
</tbody>
</table>

### Table 2. Details of soil cores studied

<table>
<thead>
<tr>
<th>Core No.</th>
<th>Depth (m)</th>
<th>Member</th>
<th>$G_s$ (°)</th>
<th>$w_l$ (%)</th>
<th>$w_p$ (%)</th>
<th>$l_p$</th>
<th>$w$</th>
<th>e₀</th>
<th>$S_r$ (%)</th>
<th>VBS</th>
<th>Carbonate content (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ess75</td>
<td>218.91-219.91</td>
<td>Putte</td>
<td>2.65</td>
<td>78</td>
<td>33</td>
<td>45</td>
<td>29.7</td>
<td>0.785</td>
<td>100</td>
<td>6.47</td>
<td>9.1</td>
</tr>
<tr>
<td>Ess83</td>
<td>226.65-227.65</td>
<td>Putte</td>
<td>2.64</td>
<td>70</td>
<td>33</td>
<td>37</td>
<td>27.2</td>
<td>0.730</td>
<td>98</td>
<td>6.67</td>
<td>7.6</td>
</tr>
<tr>
<td>Ess96</td>
<td>239.62-240.62</td>
<td>Terhagen</td>
<td>2.68</td>
<td>69</td>
<td>33</td>
<td>36</td>
<td>26.5</td>
<td>0.715</td>
<td>99</td>
<td>6.20</td>
<td>2.4</td>
</tr>
<tr>
<td>Ess104</td>
<td>247.90-248.91</td>
<td>Terhagen</td>
<td>2.68</td>
<td>68</td>
<td>29</td>
<td>39</td>
<td>27.7</td>
<td>0.700</td>
<td>100</td>
<td>6.67</td>
<td>43.6</td>
</tr>
</tbody>
</table>

### Table 3. Salts used to prepare the synthetic pore-water (concentration g/L)

<table>
<thead>
<tr>
<th>Salt</th>
<th>Ess75</th>
<th>Ess83</th>
<th>Ess96</th>
<th>Ess104</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaHCO₃</td>
<td>3.009</td>
<td>3.009</td>
<td>3.009</td>
<td>3.009</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>3.460</td>
<td>3.712</td>
<td>4.126</td>
<td>4.392</td>
</tr>
<tr>
<td>KCl</td>
<td>0.229</td>
<td>0.229</td>
<td>0.229</td>
<td>0.229</td>
</tr>
<tr>
<td>CaCl₂·2H₂O</td>
<td>0.367</td>
<td>0.385</td>
<td>0.422</td>
<td>0.459</td>
</tr>
<tr>
<td>MgCl₂·6H₂O</td>
<td>1.381</td>
<td>1.464</td>
<td>1.632</td>
<td>1.757</td>
</tr>
<tr>
<td>NaCl</td>
<td>14.542</td>
<td>15.976</td>
<td>18.002</td>
<td>19.287</td>
</tr>
</tbody>
</table>
### Table 4 Fitting expressions from test results

<table>
<thead>
<tr>
<th>No.</th>
<th>Core</th>
<th>Fitting expressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ess75</td>
<td>( k = 0.015 \times 10^{3.2e} (10^{-12} \text{ m/s}) )</td>
</tr>
<tr>
<td>2</td>
<td>Ess83</td>
<td>( k = 0.013 \times 10^{3.3e} (10^{-12} \text{ m/s}) )</td>
</tr>
<tr>
<td>3</td>
<td>Ess96</td>
<td>( k = 0.020 \times 10^{3.2e} (10^{-12} \text{ m/s}) )</td>
</tr>
<tr>
<td>4</td>
<td>Ess104</td>
<td>( k = 0.038 \times 10^{2.9e} (10^{-12} \text{ m/s}) )</td>
</tr>
</tbody>
</table>

### Table 5. Mean value of \( R \) (a) and the root mean square error of \( R \) (b)

<table>
<thead>
<tr>
<th>Equation No.1</th>
<th>Equation No.2</th>
<th>Equation No.3</th>
<th>Equation No.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ess75</td>
<td>0.6</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Ess83</td>
<td>1.1</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Ess96</td>
<td>0.8</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Ess104</td>
<td>0.7</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Mol</td>
<td>0.7</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>All data</td>
<td>0.8</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ess75</td>
<td>0.5</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Ess83</td>
<td>0.4</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Ess96</td>
<td>0.5</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Ess104</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Mol</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>All data</td>
<td>0.5</td>
<td>0.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Figure 1. Location of the Essen site and Mol site (De Craen et al., 2006)

Figure 2. Particle size distribution of Boom clay at Essen
Figure 3. Relationship between water volume change and elapsed time by the constant-head method for Ess83 and Ess96
Figure 4. Void ratio versus effective vertical stress for oedometer and isotropic consolidation tests on Ess83
Figure 5. Hydraulic conductivity versus void ratio obtained with three methods for Ess83
Figure 6. Relationships between hydraulic conductivity and void ratio; (a) Ess75, (b) Ess83, (c) Ess96, (d) Ess104.
Figure 7. Predicted hydraulic conductivity versus experimental one – models with known \( k_0 \);

(a) Ess75, (b) Ess83, (c) Ess96, (d) Ess104, (e) Mol, (f) all data
Figure 8. Predicted hydraulic conductivity versus experimental one – models without $k_0$; (a) Equation No. 2, (b) Equation No. 4
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Figure 10. Relationship between $C_k$ and initial void ratio $e_0$