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Study on the hydraulic conductivity of Boom clay

Yong-Feng Deng[1, 2], Anh-Minh Tang[2], Yu-Jun Cui[2], Xiang-Ling Li[3]

[1] Southeast University, Institute of Geotechnical Engineering, Transportation College, Nanjing, China
[2] Ecole des Ponts ParisTech, Navier/CERMES, Marne-la-Vallée, France
[3] Euridice Group, c/o SCK/CEN, Mol, Belgium

Corresponding author

Prof. Yu-Jun CUI
Ecole des Ponts ParisTech, Navier/CERMES
6-8 av. Blaise Pascal, Cité Descartes, Champs-sur-Marne
F-77455 MARNE-LA-VALLEE CEDEX 2
France

Email: yujun.cui@enpc.fr
Tel: +33 1 64 15 35 50
Fax: +33 1 64 15 35 62

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 3×10^{-12} to 10×10^{-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 γ is the unit weight of the fluid involved; μ is the viscosity of the fluid, C_{K-C} is the Kozeny-Carman empirical coefficient and S_0 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_0 and e_0 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.* (1990*a*, 1990*b*) 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 µm) 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, 2005*a*).

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, 2005*a*).

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 1.23×10^{-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 2.46×10^{-12} m/s (at a void ratio of 0.640); For Ess96, the seepage velocity is 1.00×10^{-8} m/s and the hydraulic conductivity k is 2.00×10^{-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 **Erreur ! 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 σ_v = 0.125 MPa (point *D*), 0.270 for σ_v = 30 MPa (point *E*), and 0.569 for σ_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 $k = 0.015 \times 10^{3.1e} (10^{-12} m/s)$.

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 6×10^{-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: $k = 0.09 \times 10^{4.1e} (10^{-12} m/s)$. 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 x 10^{-12} m/s and 5 × 10^{-12} m/s, with a value of 2.5 × 10^{-12} 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 × 10^{-12} m/s and 2.1× 10^{-12} m/s, with a value of 2.0 × 10^{-12} 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 $k = Cf(e)$, 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 $k = Ce^4$ (from equation No. 4), where C can be calculated using k_0 and e_0 as $C = k_0 / f(e_0)$.

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 ($b = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(R_i - 1)^2}$); where R is defined as the ratio of the predicted value $k_{predicted}$ to the calculated experiment value $k_{calculated}$ and N 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 $k = k_0 \times 10^{\frac{e-e_0}{0.5e_0}}$ and $k = \frac{k_0}{e_0^4} e^4$, 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):

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

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

[2] $$k = \frac{5.0\times 10^{-5}}{\gamma_s^2 w_L^{2.9}} \frac{e^3}{1+e} \quad \text{(m/s)}$$

where γ_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* ($k_{predicted}/k_{calculated}$) 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 ca 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.*, 1990*a*, 1990*b*; Nagaraj and Miura, 2001), while equation No. 2 presents the advantage of estimating parameter *C* without measuring k_0. As $C_{K\text{-}C}$ in equation No. 2 is a function of $w_L^{2.9}$, the following equation can be then proposed:

[3] $$k = \frac{A}{w_L^{2.9}} \times 10^{Be} (m/s)$$

Where *A* and *B* are two constants. In the case of Boom clay, the back analysis gives: $A = 3.2\times10^{-9}$ (m/s) 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] (0.9×10^{-12} - 4.4×10^{-12} m/s) covers the range of the hydraulic conductivity of Boom clay (1.2×10^{-12} - 4.2×10^{-12} 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 $k = \frac{A}{w_L^{2.9}}\times10^{Be}(m/s)$ has been proposed for Boom clay with $A = 3.2\times10^{-9}$ 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 γ_s of Boom clay equal to

2.68 kN/m^3, this equation ($k = \frac{5.0\times10^{-7}\gamma_s^2}{\mathrm{w}_\mathrm{L}^{2.9}}\frac{\mathrm{e}^3}{1+\mathrm{e}}$) allows parameter A to be deduced: $A = 7.0\times10^{-6}$. 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:

$$k = k_0 \times 10^{\frac{e-e_0}{0.5e_0}} \quad \text{and} \quad k = \frac{k_0}{e_0^4}e^4$$

(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:

$$k = \frac{5.0\times10^{-5}}{\gamma_s^2 w_L^{2.9}}\frac{e^3}{1+e}$$

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

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

$$k = \frac{3.2\times10^{-9}}{W_L^{2.9}}10^{3.56e}$$

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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Table 1. Correlations between hydraulic conductivity and void ratio

Eq. No.	Proponent	Correlations	Soil type	References
1	Taylor (1948)	$k = C\frac{e^m}{1+e}$	Sand and clay	Indraratna and Rujikiatkamjorn (2004)
2	Kozeny (1927) and Carman (1938, 1956)	$k = \frac{\gamma}{\mu C_{K-C} S_0^2}\frac{e^3}{1+e}$	Porous materials	David (2003)
3	Taylor (1948)	$k = k_0 \times 10^{\frac{e-e_0}{C_k}}, C_k = 0.5e_0$	Soft Clay	Indraratna and Rujikiatkamjorn (2004)
4	Mesri et al. (1994)	$k = 6.54\times10^{-11}(\frac{e/CF}{A_c+1})^4$	Soft Clay	Mesri *et al.* (1994)

Table 2. Details of soil cores studied

Core No.	Depth (m)	Member	G_s	w_L (%)	w_p (%)	I_p	w	e_0	S_r (%)	VBS	carbonate content (g/kg)
Ess75	218.91-219.91	Putte	2.65	78	33	45	29.7	0.785	100	6.47	9.1
Ess83	226.65-227.65	Putte	2.64	70	33	37	27.2	0.730	98	6.67	7.6
Ess96	239.62-240.62	Terhagen	2.68	69	33	36	26.5	0.715	99	6.20	2.4
Ess104	247.90-248.91	Terhagen	2.68	68	29	39	27.7	0.700	100	6.67	43.6

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

Salt	Ess75	Ess83	Ess96	Ess104
$NaHCO_3$	3.009	3.009	3.009	3.009
Na_2SO_4	3.460	3.712	4.126	4.392
KCl	0.229	0.229	0.229	0.229
$CaCl_2.2H_2O$	0.367	0.385	0.422	0.459
$MgCl_2.6H_2O$	1.381	1.464	1.632	1.757
NaCl	14.542	15.976	18.002	19.287

Table 4 Fitting expressions from test results

No.	Core	Fitting expressions
1	Ess75	k=0.015×10$^{3.2e}$ (10^{-12} m/s)
2	Ess83	k=0.013×10$^{3.3e}$ (10^{-12} m/s)
3	Ess96	k=0.020×10$^{3.2e}$ (10^{-12} m/s)
4	Ess104	k=0.038×10$^{2.9e}$ (10^{-12} m/s)

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

		Equation No.1	Equation No.2	Equation No.3	Equation No.4
a	Ess75	0.6	1.8	1.3	1.1
	Ess83	1.1	1.7	1.3	1.1
	Ess96	0.8	1.4	1.1	1.0
	Ess104	0.7	1.3	1.0	0.8
	Mol	0.7	1.1	0.9	0.8
	All data	0.8	1.4	1.1	0.9
b	Ess75	0.5	1.2	0.7	0.4
	Ess83	0.4	0.9	0.6	0.4
	Ess96	0.5	0.8	0.4	0.4
	Ess104	0.5	0.5	0.3	0.4
	Mol	0.5	0.4	0.3	0.5
	All data	0.5	0.8	0.4	0.4

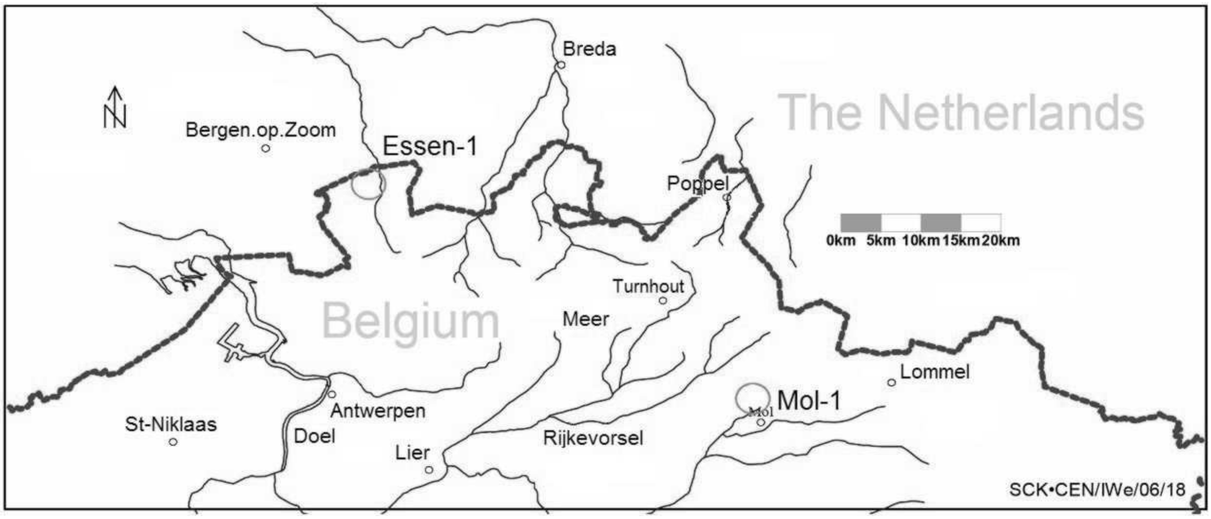


Figure 1. Location of the Essen site and Mol site (De Craen et al., 2006)

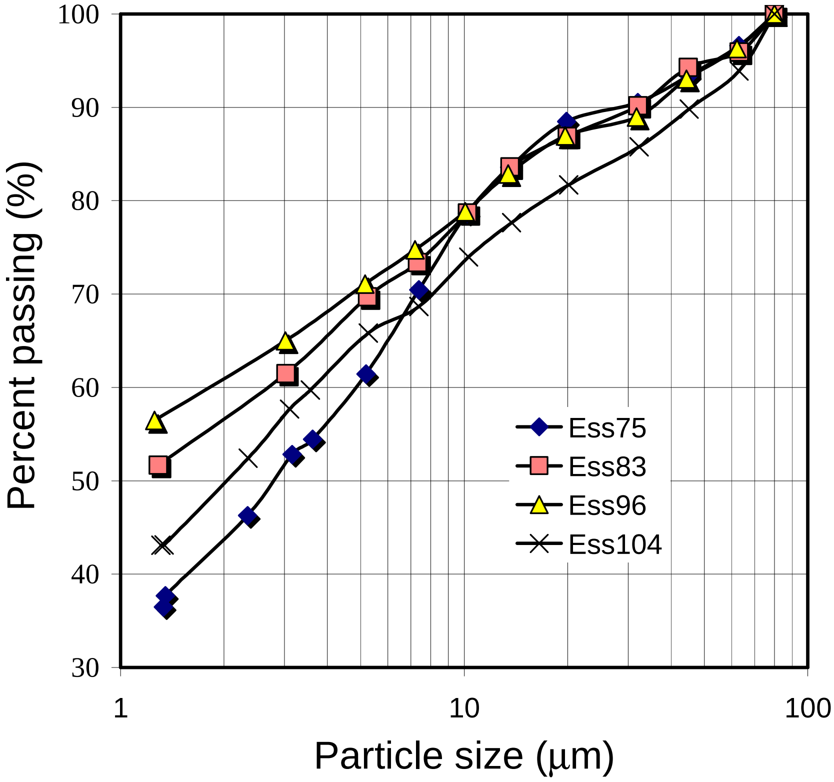


Figure 2. Particle size distribution of Boom clay at Essen

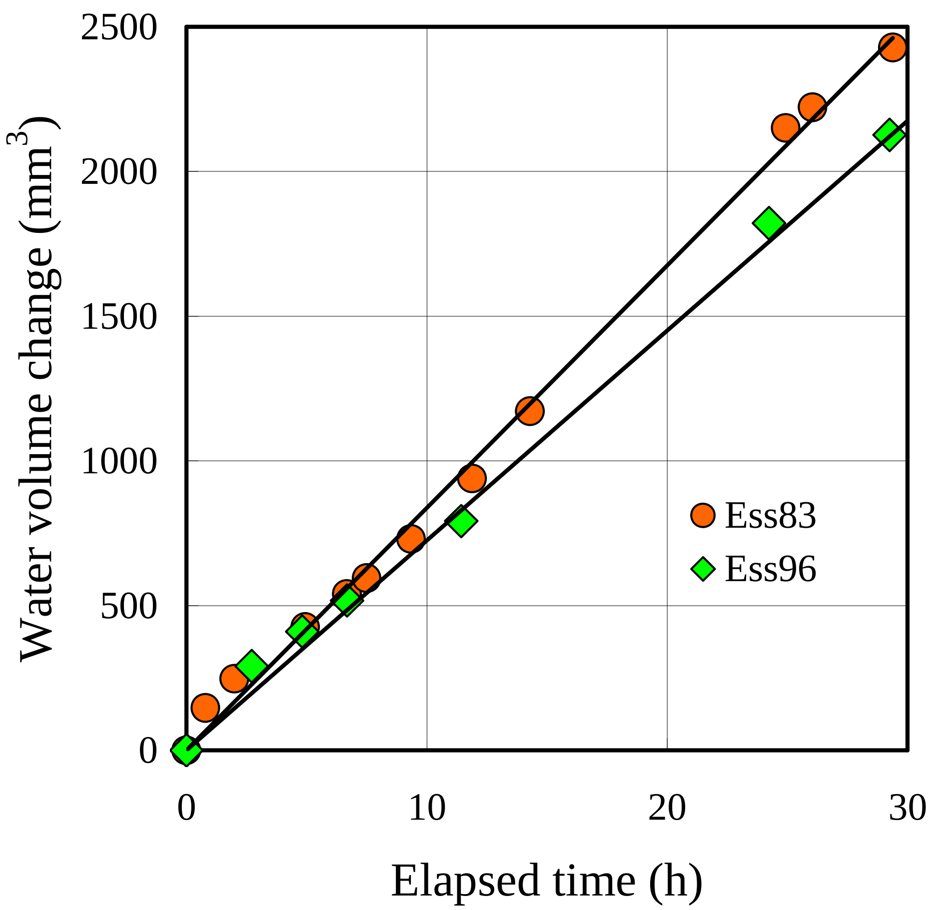


Figure 3. Relationship between water volume change and elapsed time by the constant-head method for Ess83 and Ess96

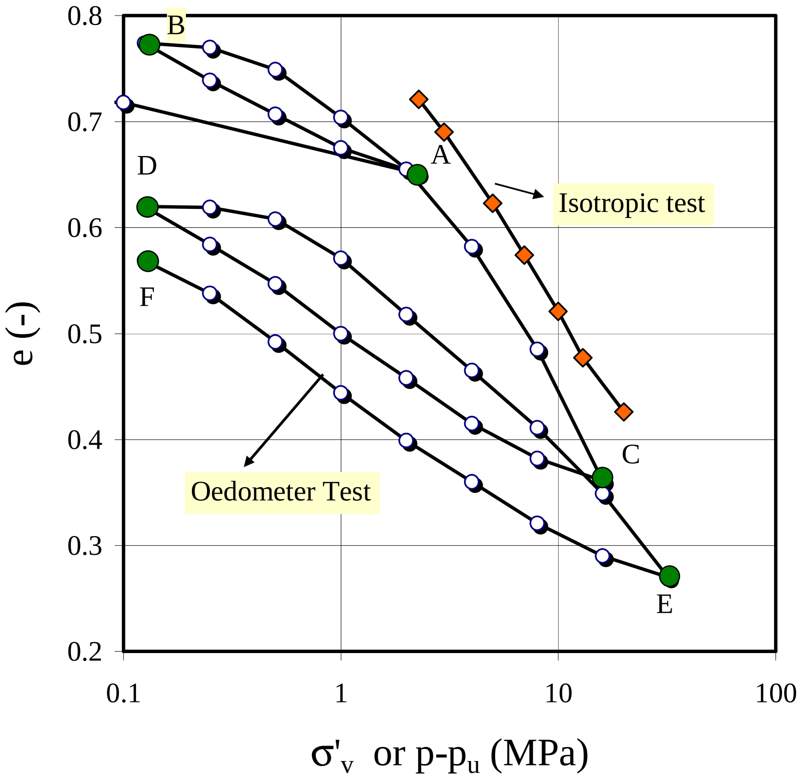


Figure 4. Void ratio versus effective vertical stress for oedometer and isotropic consolidation tests onEss83

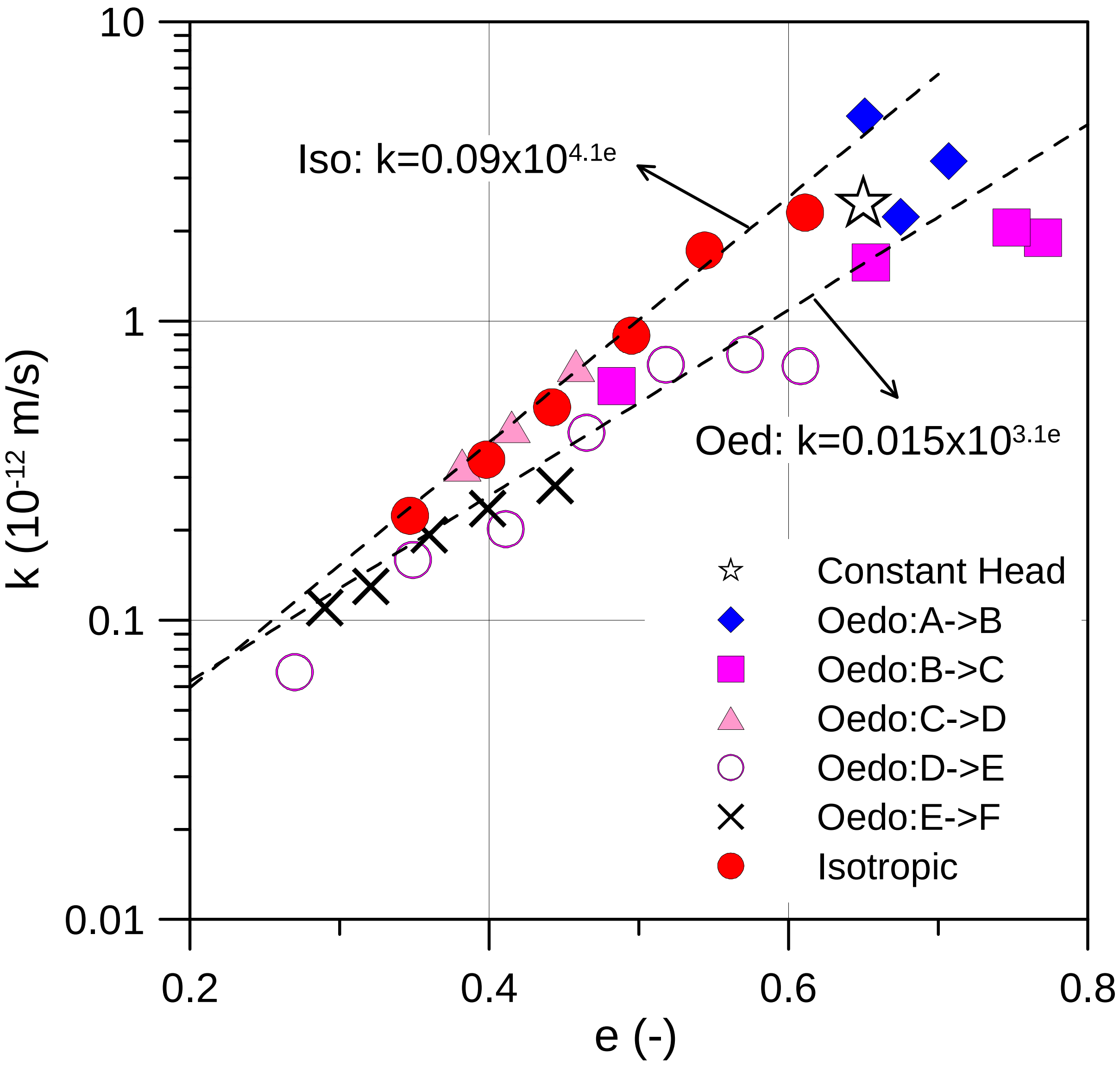


Figure 5. Hydraulic conductivity versus void ratio obtained with three methods for Ess83

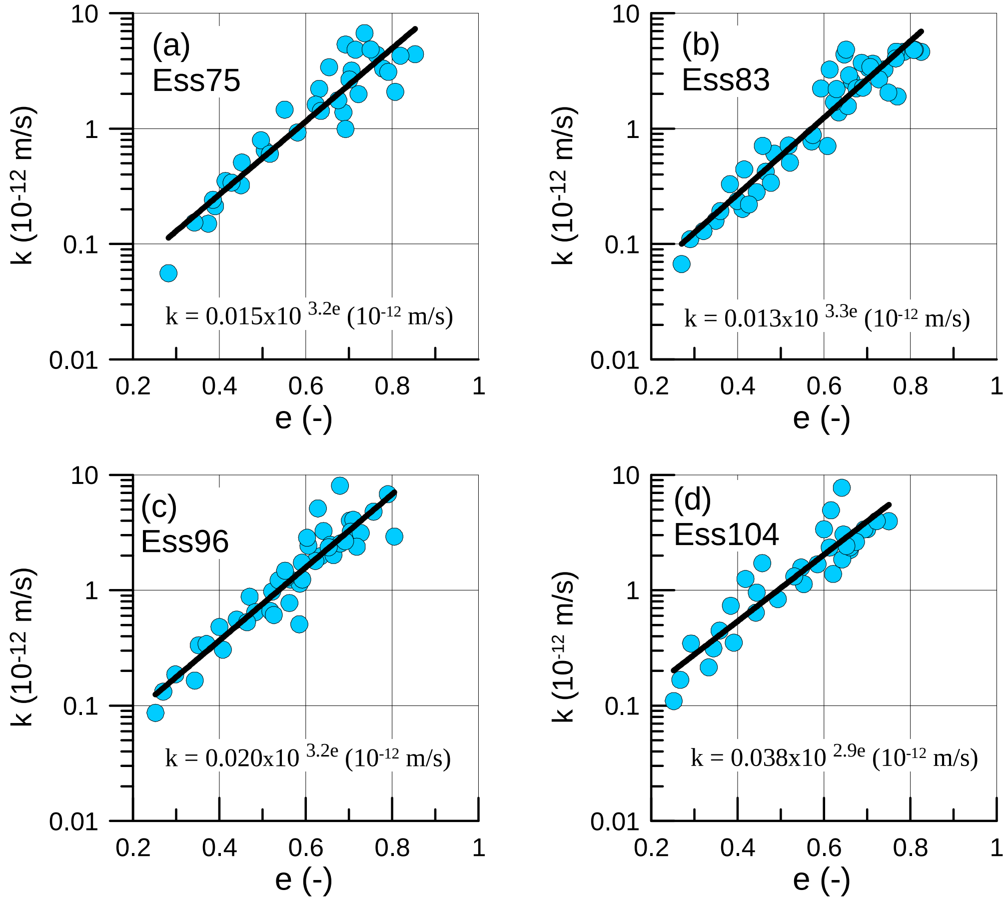


Figure 6. Relationships between hydraulic conductivity and void ratio; (a) Ess75, (b) Ess83, (c) Ess96, (d) Ess104

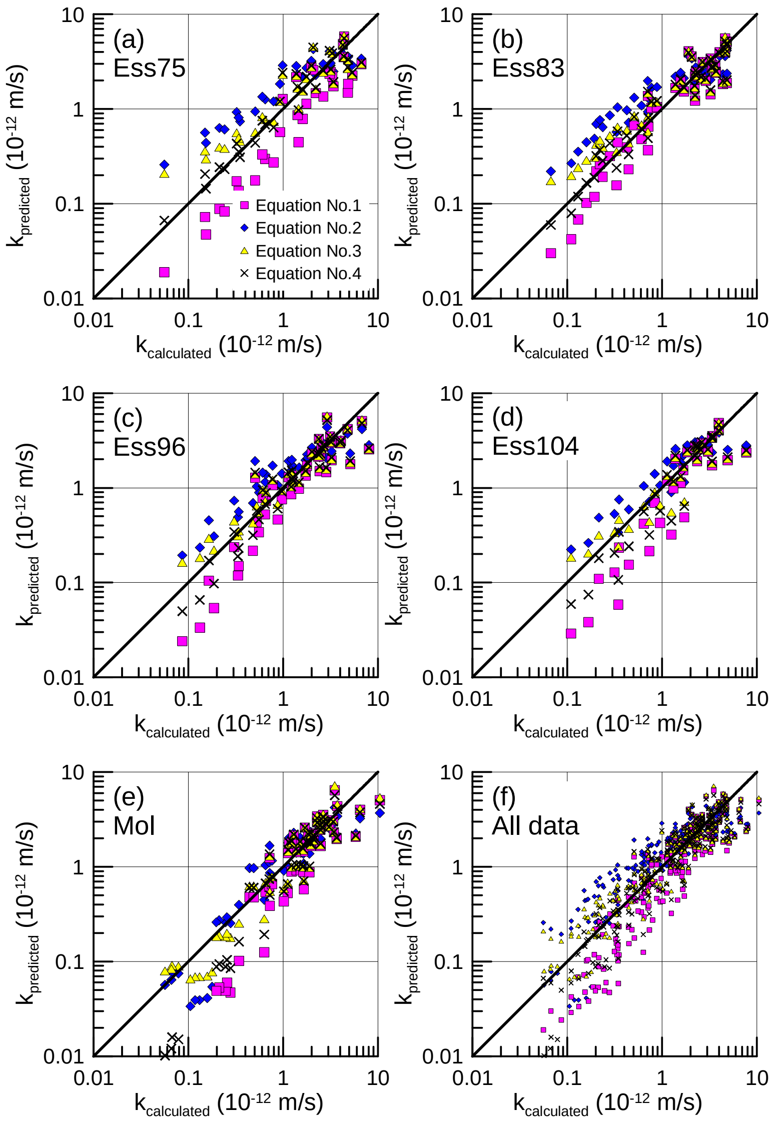
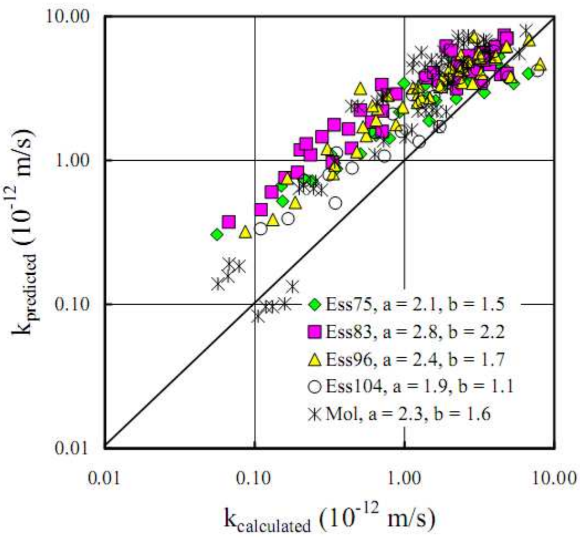
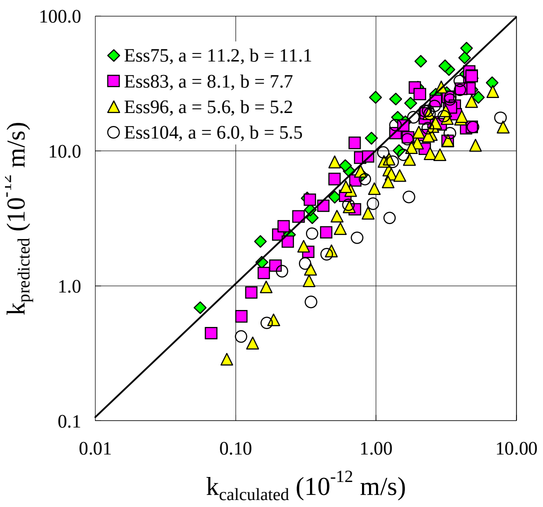


Figure 7. Predicted hydraulic conductivity versus experimental one – models with known k_0; (a) Ess75, (b) Ess83, (c) Ess96, (d) Ess104, (e) Mol, (f) all data



(a)



(*b*)

Figure 8. Predicted hydraulic conductivity versus experimental one – models without k_0; (a) Equation No. 2, (b) Equation No. 4

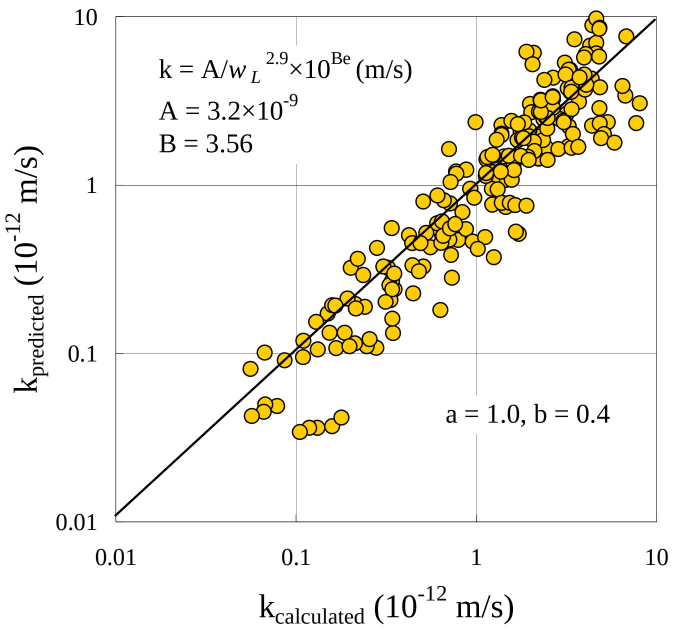


Figure 9. Hydraulic conductivity predicted by the proposed correlation versus the experimental one

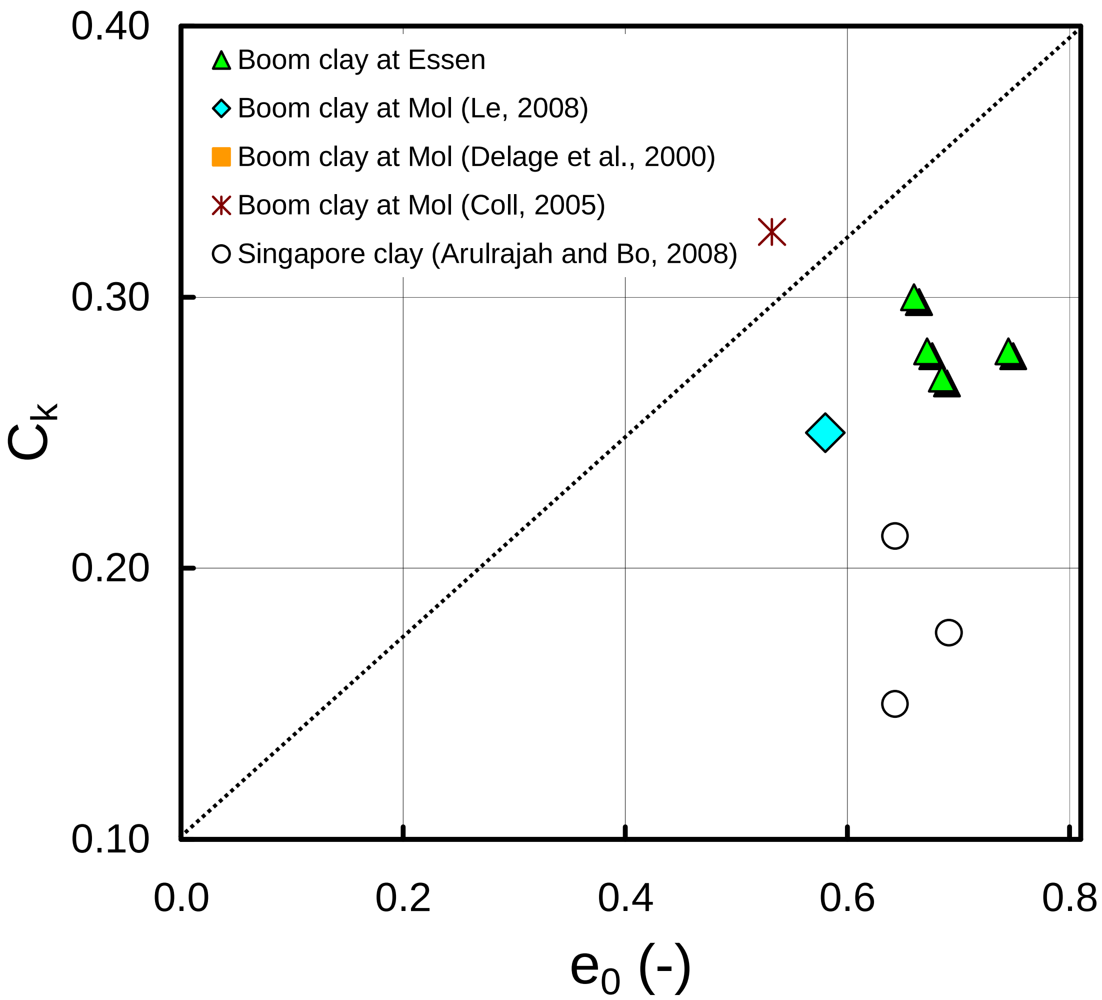


Figure 10. Relationship between C_k *and initial void ratio* e_0