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1                                    **Study on the hydraulic conductivity of Boom clay**

2  
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1    **Abstract**

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

16

17   **Keywords:** Boom clay; consolidation; constant-head percolation; hydraulic conductivity;  
18   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  $S_0$  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.* (1990a, 1990b) applied equation No. 3 to soft

1 clays with a wide range of void ratios, and proposed that  $C_k$  is a function of the in-situ void  
2 ratio  $e_0$ :  $C_k = 0.5e_0$ . Mesri *et al.* (1994) analyzed the data of soft clays and proposed  
3 equation No. 4 where  $CF$  is clay fraction and  $A_c$  is soil activity. Although there are various  
4 correlations proposed, equation No. 3 is usually used to describe the variation of hydraulic  
5 conductivity of clays versus void ratio changes. Note that these equations have been only  
6 validated for soft clays whose in-situ void ratio ( $e_0$ ) is larger than 1.0. The validation of these  
7 equations for stiff clays with a void ratio often lower than 1.0, remains to be verified.  
8

9 In the present work, the hydraulic conductivity of Boom clay cores of low in-situ void  
10 ratio ( $e_0 < 0.79$ ) taken from a borehole drilled in Essen (Belgium) was determined from  
11 oedometer and isotropic consolidation tests as well as constant-head percolation tests. Four  
12 depths in the range of 220 – 250 m were investigated. The obtained results were used to  
13 evaluate the existing correlations listed in Table 1. A new method was developed allowing  
14 prediction of the hydraulic conductivity of stiff clays using the void ratio and the liquid limit.  
15 This method was verified using the experimental results from Boom clay samples taken from  
16 various locations.  
17

## 18 2 Soils studied

19 The soil cores studied were taken from the borehole drilled in Essen (Belgium). The  
20 Essen site situates in the north east of Belgium, 60 km far from the underground research  
21 laboratory (URL) at the Mol site (Figure 1). The Boom clay formation ranged from 153 to  
22 280-m in depth. It can be sub-divided into four zones: Transition zone (153 – 200 m); Putte  
23 member (200 – 238 m); Terhagen Member (238 – 260 m); and Belsele-Waas Member (260 –  
24 280 m).  
25

26 Four cores with 1 m in length and 100 mm in diameter were studied. After being taken  
27 from the borehole, the cores were sealed in plastic tubes with ends closed and transported to  
28 the laboratory for testing. The details of these cores are shown in Table 2. Two cores were  
29 taken from the Putte member (Ess75 and Ess83) and two others from the Terhagen members  
30 (Ess96 and Ess104). The geotechnical identification parameters of these cores are similar:  
31 specific gravity,  $G_s = 2.64 - 2.68$ ; liquid limit,  $w_L = 68 - 78\%$ ; plastic limit,  $w_P = 29 - 33\%$ ;  
32 plastic index,  $I_P = 36 - 45$ . The water content ( $w$ ) ranges between 26.5 and 29.7 %, and the  
33 void ratio ( $e$ ) between 0.700 and 0.785. The values of degree of saturation ( $S_r$ ) determined in  
34 the laboratory on the cores are equal or close to 100%. The Blue Methylene value (VBS) is  
35 equally similar,  $VBS = 6.20 - 6.67$ . According to the relationship between the specific surface  
36 area (SSA) and VBS (Yukselen and Kaya, 2008), the SSA of Boom clay ranges from 152 to  
37  $163 \text{ m}^2/\text{g}$ . Nevertheless, the carbonate content of core Ess104 (43.6 g/kg) is significantly  
38 higher than that of other cores (lower than 10 g/kg). The particle size distribution determined  
39 is shown in Figure 2. The curves obtained for the four depths are similar and the clay content  
40 ( $< 2 \mu\text{m}$ ) is quite high (more than 40%). Note that the particle size distribution of Boom clay

1 at Essen is very similar to that presented by Wemaere *et al.* (2008) for Boom clay taken from  
2 other regions in Belgium (Mol, Doel, Zoersel and Weelde).

### 3 Experimental techniques

4 Three methods were used to study the hydraulic conductivity of the soil cores: (1)  
5 constant-head method using an oedometer cell; (2) back-analysis of consolidation tests in an  
6 oedometer cell; (3) Back-analysis of consolidation tests in an isotropic cell. A synthetic  
7 solution having a similar chemical composition as the in-situ pore-water was used to perform  
8 the tests. In Table 3, the composition of salts used for preparing the synthetic solution is  
9 presented for all depths. A high concentration of NaCl (15 – 20 g/L) can be observed. More  
10 details on the pore-water chemistry of Boom clay at Essen can be found in De Craen *et al.*  
11 (2006).

12  
13 For the tests in the oedometer cell, a 40 mm long section was cut from the soil core using  
14 a metal saw. The confining ring of the oedometer cell having a sharp edge was then pushed  
15 into the soil sample. The surfaces of the soil specimen were finished using a steel knife with  
16 sharp edge. The final dimension of the soil specimen is 20 mm high and 50 mm in diameter.  
17 Note that special attention was paid to sampling direction: the axis of specimens is  
18 perpendicular to the bedding plan. The confining ring having the soil specimen inside was  
19 then installed in the oedometer cell. For tests using the isotropic cell, the soil specimen was  
20 carefully hand-trimmed to have a final dimension of 38 mm in diameter and 76 mm high. The  
21 axis of the specimen is also perpendicular to the bedding plane.

22  
23 When applying the constant-head test in the oedometer cell, a vertical stress equal to the  
24 in-situ vertical stress estimated from the soil densities and depths was applied after  
25 installation of the soil specimen in the cell. The specimen was fully saturated and this was  
26 checked by considering the initial degree of saturation (see Table 2) and the volume changes  
27 due to the in-situ stress application. After stabilization of the soil deformation under this  
28 initial load, the porous stone in the base of the cell was fully saturated by the synthetic  
29 solution flushing. It was observed that this operation did not induce any volume change of the  
30 soil. A water pressure of 1.0 MPa was then applied using a controller of pressure/volume  
31 (CPV) from the lower base of the cell; the upper base was kept at atmospheric pressure. The  
32 hydraulic conductivity of the soil was calculated from the water volume change recorded by  
33 the CPV with Darcy's law. Two tests were performed using this method on core Ess83 (227 m  
34 depth) and Ess96 (239 m depth). The in-situ vertical stress was estimated to be 2.27 MPa,  
35 based on a mean value of the unit weight estimated at 20 kN/m<sup>3</sup> and a ground water level  
36 considered at the ground surface. In the oedometer test, a value of 2.40 MPa was chosen to  
37 represent the in-situ vertical stress.

38  
39 To apply the second method, one oedometer consolidation test was carried out on each of  
40 the four cores of Table 2. A vertical stress equal to the in-situ stress was applied to the  
41 specimen after its installation inside the cell. After stabilization of the volume change, the  
42 subsequent saturation of the drainage system was performed without inducing any volume

1 change of soil. The soil was then subjected to several unloading/loading paths in steps with  
2 vertical stresses ranging from 0.05 to 32 MPa. The hydraulic conductivity was finally  
3 determined following the Casagrande's method (AFNOR, 2005a).

4  
5 To apply the third method, one isotropic consolidation test was carried out on each of the  
6 four cores of Table 2. The high-pressure isotropic cell described by Cui *et al.* (2009) was used  
7 for this purpose. After installation of the soil sample on the pedestal with dry porous stones, a  
8 confining pressure equal to the in-situ stress was applied. After stabilization of the soil  
9 volume change, the drainage system was fully saturated by the synthetic solution. As in the  
10 case of oedometer tests, no volume change was observed during this operation. Later, the  
11 confining pressure and the back pressure were then increased at the same time by a same  
12 pressure increment. The final back pressure was equal to 1.0 MPa and the effective pressure  
13 of the soil was still equal to the in situ stress. After Delage *et al.* (2007), this procedure allows  
14 a satisfactory saturation of the soil sample without disturbing its initial state (in terms of  
15 microstructure and stress state). Finally, the confining pressure was incrementally increased,  
16 allowing the determination of the hydraulic conductivity at various void ratios following  
17 Casagrande's method (AFNOR, 2005a).

## 19 4 Experimental results

20 In Figure 3, the results obtained from the test using the constant-head method are shown.  
21 The volume of solution passing through the soil specimen (20 mm high) under a pressure  
22 gradient of 1.0 MPa is plotted versus time. For Ess83, a seepage velocity of  $1.23 \times 10^{-8}$  m/s  
23 can be determined and the hydraulic gradient  $i$  being 5000 (water head divided by sample  
24 height), hence the hydraulic conductivity  $k$  is  $2.46 \times 10^{-12}$  m/s (at a void ratio of 0.640); For  
25 Ess96, the seepage velocity is  $1.00 \times 10^{-8}$  m/s and the hydraulic conductivity  $k$  is  
26  $2.00 \times 10^{-12}$  m/s (at a void ratio of 0.586. Note that during this step, no obvious vertical  
27 deformation was observed for both samples.

28  
29  
30 Using the results from the oedometer test on Ess83, the relationship between the  
31 calculated void ratio and the corresponding vertical stress can be obtained as shown in  
32 **Erreur ! Source du renvoi introuvable.** The initial loading to the in-situ stress decreased the  
33 void ratio from 0.730 to 0.651 (point A). The saturation of the drainage system did not induce  
34 significant change in void ratio. The subsequent unloading in steps to 0.125 MPa increased  
35 the void ratio up to 0.774 (point B). After the loading in steps to 16 MPa, the void ratio  
36 decreased to 0.361 (point C). For the subsequent paths, the void ratios were equal to 0.620 for  
37  $\sigma_v = 0.125$  MPa (point D), 0.270 for  $\sigma_v = 30$  MPa (point E), and 0.569 for  $\sigma_v = 0.125$  MPa  
38 (point F). Note that the volume change was considered as stabilized when the deformation

1 rate was less than 0.00125 mm/h following the French standard (AFNOR, 1995). It can be  
2 observed that the time needed for the stabilization during the unloading steps was generally  
3 longer than during the loading steps. A total of about 80 days was needed to finish the  
4 oedometer test.

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

12  
13 The results of the isotropic consolidation test on Ess83 are also shown in Figure 4, in  
14 terms of variations of void ratio as a function of effective pressure. It can be observed that  
15 from the in-situ stress of 2.40 MPa (initial void ratio of 0.725), loading in steps up to 20 MPa  
16 effective pressure decreased the void ratio to 0.426. Moreover, the relationship between void  
17 ratio and the logarithm of  $(p-p_u)$  can be described with a linear correlation. This corresponds  
18 to the compression curve of a normally consolidated soil with a compression index  $C_c$  equal  
19 to 0.31. It should be noted that in this test each loading step was maintained until stabilization  
20 of the volumetric strain according to the French standard (AFNOR, 2005b): the volumetric  
21 strain rate should be less than  $6 \times 10^{-5}/h$ . The time needed for each step varied from 100 h to  
22 250 h. A total of 40 days was needed to finish the test.

23  
24 The hydraulic conductivity using the third method (back analysis from the consolidation  
25 tests using the high-pressure isotropic cell) was also presented in Figure 5, versus void ratio.  
26 As observed in the case of the consolidation test in the oedometer cell, a linear function can  
27 be proposed to correlate the relationship between void ratio and the logarithm of hydraulic  
28 conductivity:  $k = 0.09 \times 10^{4.1e} (10^{-12} m/s)$ . This expression is similar to that obtained from the  
29 oedometer test.

30  
31 In order to evaluate the three methods used for the hydraulic conductivity determination,  
32 the result of Ess83 obtained by the first method is also presented in Figure 5. It can be  
33 observed that similar results were obtained by the three methods: the hydraulic conductivity at  
34 a void ratio of 0.64 is between  $1.5 \times 10^{-12} m/s$  and  $5 \times 10^{-12} m/s$ , with a value of  $2.5 \times 10^{-12} m/s$   
35 obtained by the constant-head method. Note that for Ess96 the three methods gave also  
36 similar results: the hydraulic conductivity at a void ratio of 0.59 is between  $0.9 \times 10^{-12} m/s$  and  
37  $2.1 \times 10^{-12} m/s$ , with a value of  $2.0 \times 10^{-12} m/s$  obtained by the constant-head method. The  
38 difference between the results by the three methods is due to both the experimental error and  
39 the heterogeneity of natural Boom clay.

40  
41 All the results obtained from Ess83 core are gathered in Figure 6b. As mentioned before, for  
42 Ess96, all the three methods (constant-head method, consolidation using the oedometer and



1 the isotropic cell, respectively) were applied. Only the second and third methods were applied  
2 for Ess75 Ess104. The results are plotted in Figure 6c for Ess96, in Figure 6a for Ess75 and in  
3 Figure 6d for Ess104. It can be observed that, on the whole, the relationship between void  
4 ratio and the logarithm of hydraulic conductivity can be satisfactorily correlated with a linear  
5 function. Furthermore, the functions obtained for Ess75, Ess83, Ess96 and Ess104 are similar  
6 (see Table 4 for all fitting equations).

## 7 **5 Prediction of hydraulic conductivity**

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

15  
16 In the following sections, the experimental data obtained on Boom clay from Essen and  
17 that from Mol (Delage *et al.*, 2000; Aertsens *et al.*, 2004; Coll, 2005; Le, 2008; Wemaere *et al.*  
18 2008) are used to assess the various models presented in Table 1. The models requiring the  
19 initial hydraulic conductivity ( $k_0$ ) and the initial void ratio ( $e_0$ ) are firstly evaluated. The two  
20 models that do not require  $k_0$  and  $e_0$  are considered afterwards. Finally, a new correlation  
21 is proposed for Boom clay.

### 22 **5.1 Evaluation of existing models requiring $k_0$ and $e_0$**

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

27  
28 In order to evaluate the predicting models, the two following parameters were calculated:

1 (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  $R$

2 ( $b = \sqrt{\frac{1}{N} \sum_{i=1}^N (R_i - 1)^2}$ ); where  $R$  is defined as the ratio of the predicted value  $k_{predicted}$  to the

3 calculated experiment value  $k_{calculated}$  and  $N$  is the statistical number (Tang *et al.* 2008).

4  
5 In Figure 7, the hydraulic conductivity values predicted by the above equations are  
6 plotted versus the calculated values for the four soil cores from Essen ( $a$ ,  $b$ ,  $c$ ,  $d$ ) and Boom  
7 clay from Mol ( $e$ ). In Figure 7f, all the data are put together for the analysis. The mean value  
8 of  $R$  and the root mean square error of  $R$  are shown in Table 5.

9  
10 It can be observed that equation No. 1 underestimates the hydraulic conductivity for  
11 almost all cores (except Ess83) with a relative large scatter ( $b = 0.5$ ). On the contrary,  
12 equation No. 2 overestimates the hydraulic conductivity for all cores with a large scatter ( $b =$   
13  $0.8$ ). Equation No. 3 and No. 4 can predict the hydraulic conductivity satisfactorily for all  
14 cores.

15  
16 As a conclusion, when  $k_0$  and  $e_0$  are available, equation No. 3 and No. 4 are suitable for  
17 predicting the hydraulic conductivity of Boom clay by modifying these equations as

18  $k = k_0 \times 10^{\frac{e-e_0}{0.5e_0}}$  and  $k = \frac{k_0}{e_0^4} e^4$ , respectively.

19

## 20 **5.2 Models without $k_0$ and $e_0$**

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

25 [1] 
$$k = Cf(e) = \frac{\gamma}{\mu C_{k-c}} \frac{1}{S_0^2} \frac{e^3}{1+e} = \frac{20000}{S_0^2} \frac{e^3}{1+e} (m/s)$$

26 where  $S_0$  is the specific surface area.

27

28 The correlation by Mbonimpa *et al.* (2002) was applied to estimate  $S_0$  from the liquid

1 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

2 area  $S_0$  of Boom clay calculated using VBS (in Table 2) according to Yuxselen and Kaya  
3 (2008) and liquid limit  $w_L$  were used to verify the correlation by Mbonimpa *et al.* (2002).  
4 With this correlation, the hydraulic conductivity expression can be rewritten as

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

6 where  $\gamma_s$  is the unit weight of soil particles.

7  
8 The above expression [2] and equation No. 4 (in Table 1) were used to predict the  
9 hydraulic conductivity of Boom clay from Essen and Mol without using  $k_0$ . The predicted  
10 values are plotted versus the calculated (or measured) values in Figure 8a (equation No. 2)  
11 and Figure 8b (equation No. 4). The parameters  $a$  and  $b$  are also presented to evaluate these  
12 models.  
13

14 From Figure 8a, it can be observed that the mean value  $a$  ( $k_{predicted} / k_{calculated}$ ) ranges from  
15 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  
16 value, the predicted hydraulic conductivity fits well with the calculated one; but if the soils  
17 are compressed and the void ratio is decreased, the hydraulic conductivity will be  
18 over-evaluated. For equation No. 4 (Figure 8b), the mean value  $a$  ranges from 5.6 to 11.2 and  
19 the error  $b$  ranges from 5.2 to 11.1. That means this equation overestimates by about 10 times  
20 the hydraulic conductivity of Boom clay.  
21

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

### 26 **5.3 A correlation for Boom clay**

27 The above evaluation shows that equation No. 3 in Table 1 is suitable for describing the  
28 relationship between  $k$  and  $e$  and has been used in various works (Leroueil *et al.*, 1990a,  
29 1990b; Nagaraj and Miura, 2001), while equation No. 2 presents the advantage of estimating  
30 parameter  $C$  without measuring  $k_0$ . As  $C_{K-C}$  in equation No. 2 is a function of  $w_L^{2.9}$ , the  
31 following equation can be then proposed:

$$32 \quad [3] \quad k = \frac{A}{w_L^{2.9}} \times 10^{Be} (m/s)$$

1 Where  $A$  and  $B$  are two constants. In the case of Boom clay, the back analysis gives:

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

3  
4 In Figure 9, the hydraulic conductivity calculated from the proposed correlation is  
5 presented versus the measured values. As the parameters were fitted using the data by back  
6 analysis, the value of  $a$  is equal to 1.0; the error  $b$  obtained is equally small,  $b = 0.4$ . Note that  
7 there are more data available for higher hydraulic conductivity than for lower conductivity,  
8 and therefore the proposed correlation is more suitable for the range of high hydraulic  
9 conductivity.

10  
11 With the proposed correlation and the values of  $w_L$  (59% - 83% ) and  $e_0$  (0.56 - 0.68)  
12 reported by François *et al.* (2009), the predicted hydraulic conductivity using expression [3]  
13 ( $0.9 \times 10^{-12}$  -  $4.4 \times 10^{-12}$  m/s) covers the range of the hydraulic conductivity of Boom clay  
14 ( $1.2 \times 10^{-12}$  -  $4.2 \times 10^{-12}$  m/s) measured by Aertsen *et al.* (2004) at Mol and by Wemaere *et al.*  
15 (2008) at Mol, Doel, Zoerel and Weedle.

## 16 6 Discussion

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

27 In this study, the correlation  $k = \frac{A}{w_L^{2.9}} \times 10^{Be}$  (m/s) has been proposed for Boom clay  
28 with  $A = 3.2 \times 10^{-9}$  and  $B = 3.56$ . Actually, from equation No. 3 (Table 1), if  $C_k$  is taken as  
29 the mean value of  $C_k$  for Boom clay ( $C_k = 0.3$ ), the  $B$  value is equal to 3.33. This value is  
30 similar to that obtained for the proposed correlation. On the other hand, the value of  $A$  can be  
31 also calculated from equation No. 2. Indeed, taking the unit weight  $\gamma_s$  of Boom clay equal to

1 2.68 kN/m<sup>3</sup>, this equation ( $k = \frac{5.0 \times 10^{-7} \gamma_s^2 e^3}{w_L^{2.9} (1+e)}$ ) allows parameter A to be deduced: A

2 = 7.0 × 10<sup>-6</sup>. This value is 2200 times larger than that obtained from the correlation [3].  
3 However, when the void ratio is equal to 0.77, the predicted hydraulic conductivity by both  
4 equation No. 2 and correlation [3] is close to the measured one.  
5

## 6 7 Conclusions

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

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

$$18 \quad k = k_0 \times 10^{\frac{e-e_0}{0.5e_0}} \quad \text{and} \quad k = \frac{k_0}{e_0^4} e^4$$

19  
20 (2) When the in-situ hydraulic conductivity is not available, the following equation can  
21 be used for stiff clay especially when the void ratio is close to the in-situ value:

$$22 \quad k = \frac{5.0 \times 10^{-5} e^3}{\gamma_s^2 w_L^{2.9} (1+e)}$$

23 This equation was verified using the experimental data on Boom clay.  
24

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

$$26 \quad k = \frac{3.2 \times 10^{-9}}{W_L^{2.9}} 10^{3.56e}$$

27 This equation was developed based on the linear correlation observed on the  
28 experimental data between the logarithm of hydraulic conductivity and void ratio. The  
29 liquid limit  $w_L$  is introduced to take into account the variable characterization of Boom  
30 clay at various locations.  
31

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5

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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)	$k = 6.54 \times 10^{-11} \left( \frac{e/CF}{A_c + 1} \right)^4$	Soft Clay	Mesri et al. (1994)

3

4

Table 2. Details of soil cores studied

Core No.	Depth (m)	Member	G <sub>s</sub>	w <sub>L</sub> (%)	w <sub>p</sub> (%)	l <sub>p</sub>	w	e <sub>0</sub>	S <sub>r</sub> (%)	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

5

6

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

Salt	Ess75	Ess83	Ess96	Ess104
NaHCO <sub>3</sub>	3.009	3.009	3.009	3.009
Na <sub>2</sub> SO <sub>4</sub>	3.460	3.712	4.126	4.392
KCl	0.229	0.229	0.229	0.229
CaCl <sub>2</sub> .2H <sub>2</sub> O	0.367	0.385	0.422	0.459
MgCl <sub>2</sub> .6H <sub>2</sub> O	1.381	1.464	1.632	1.757
NaCl	14.542	15.976	18.002	19.287

7

8

1

Table 4 Fitting expressions from test results

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

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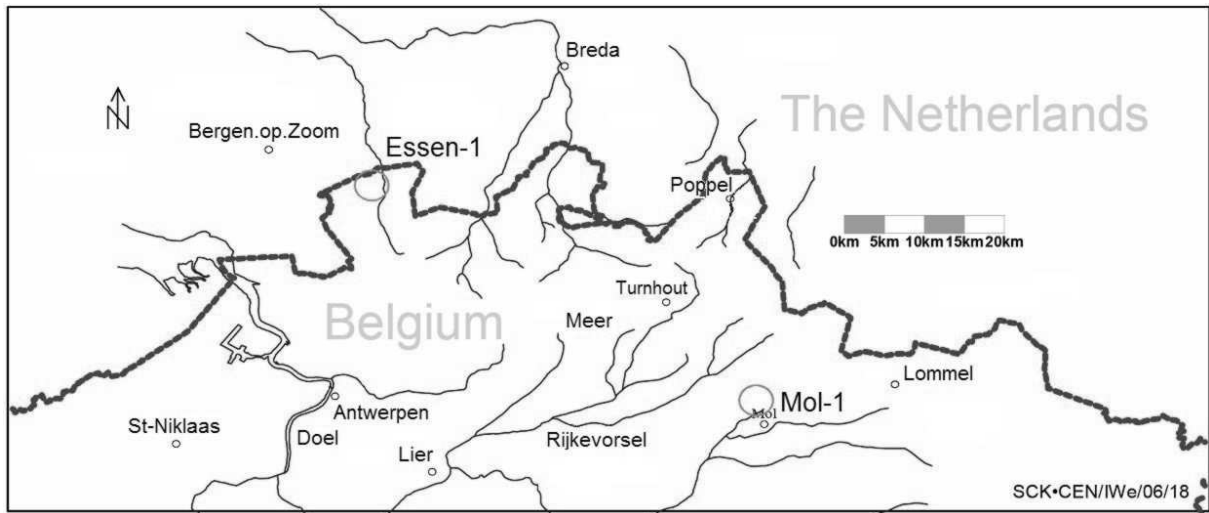
Table 5 . Mean value of R (a) and the root mean square error of R (b)

5

		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

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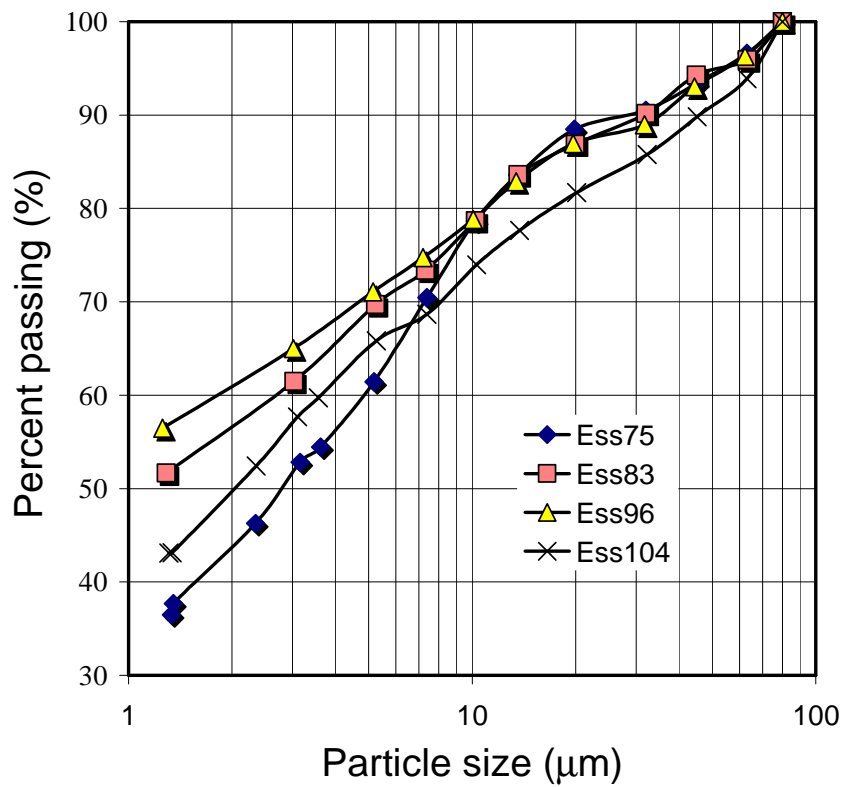
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2 *Figure 1. Location of the Essen site and Mol site (De Craen et al., 2006)*

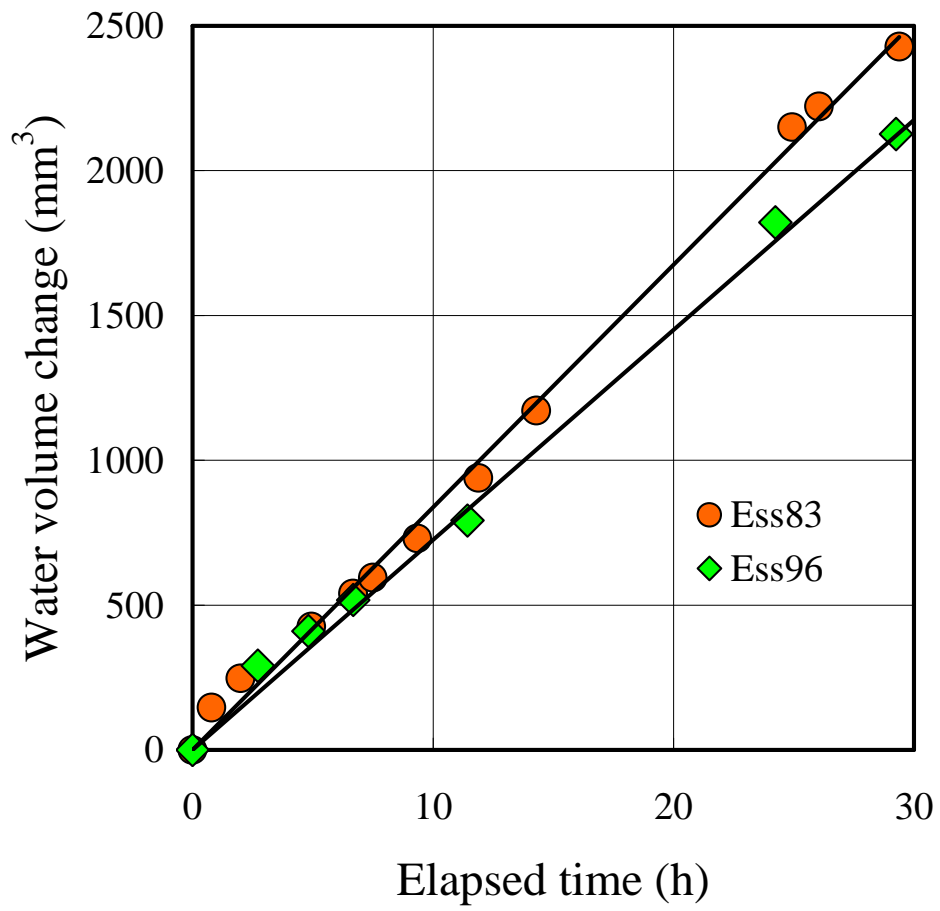
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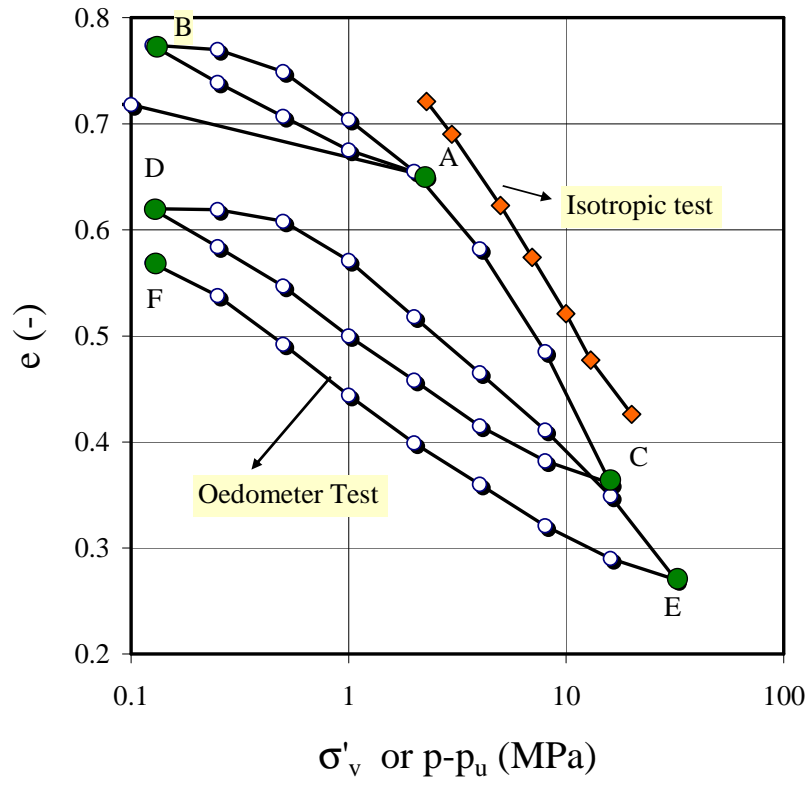
5 *Figure 2. Particle size distribution of Boom clay at Essen*

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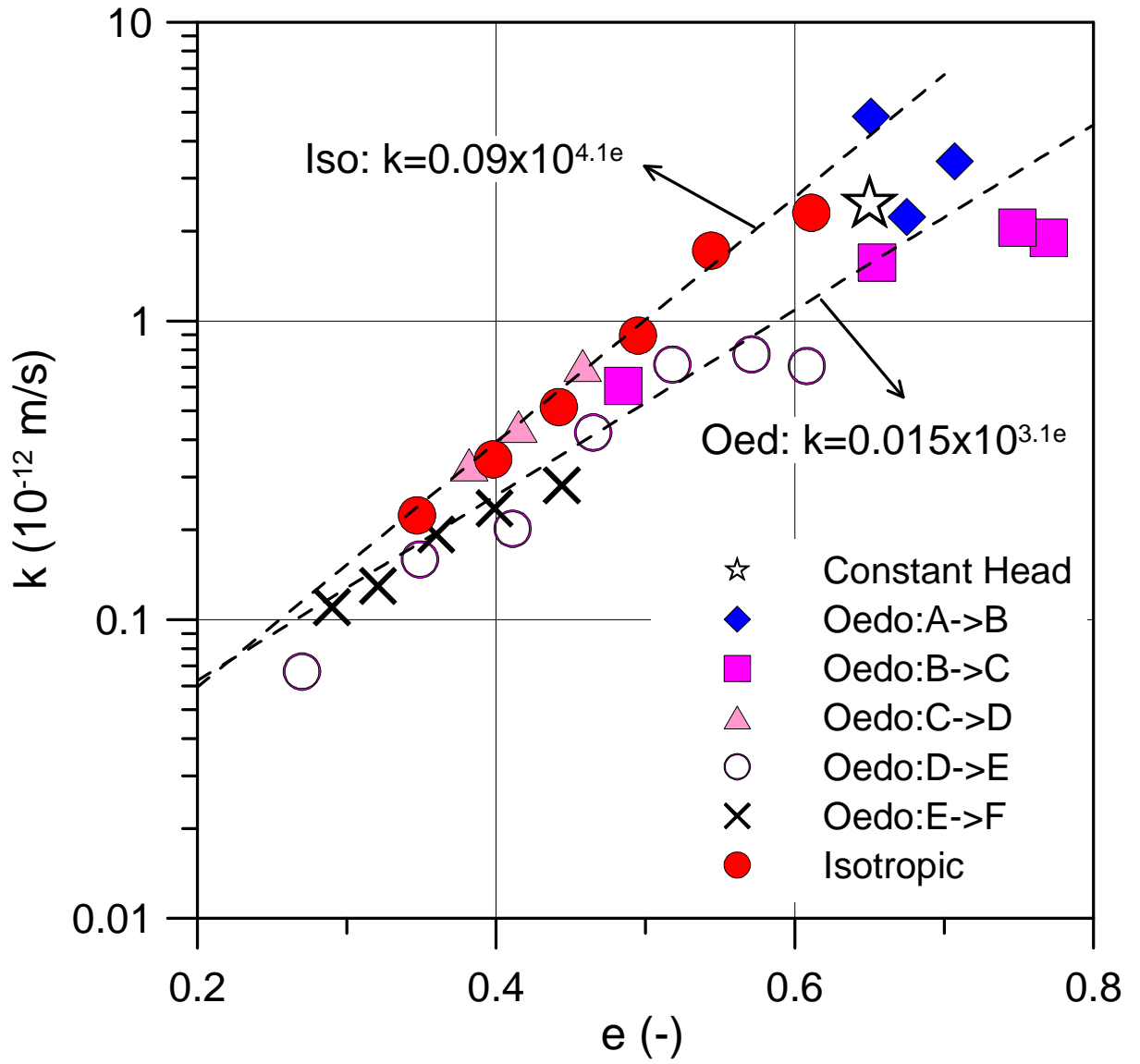
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2 *Figure 3. Relationship between water volume change and elapsed time by the constant-head*  
 3 *method for Ess83 and Ess96*



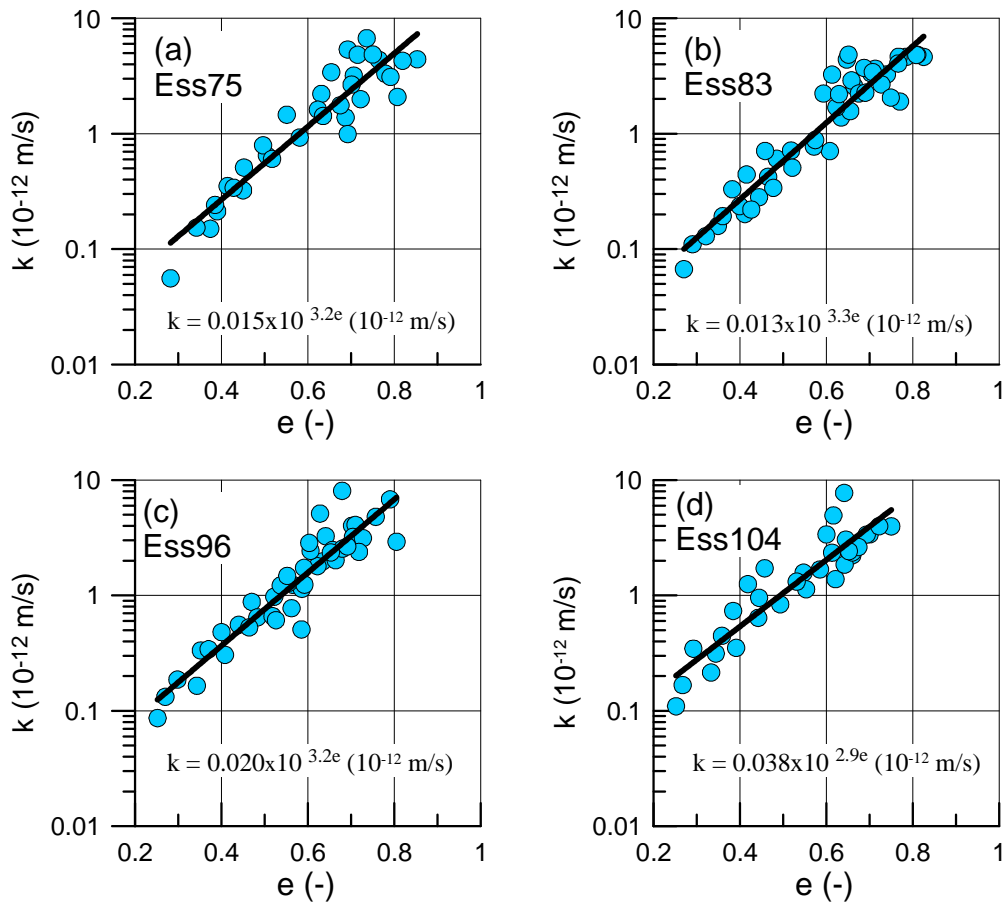
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2 *Figure 4. Void ratio versus effective vertical stress for oedometer and isotropic consolidation*  
 3 *tests onEss83*



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



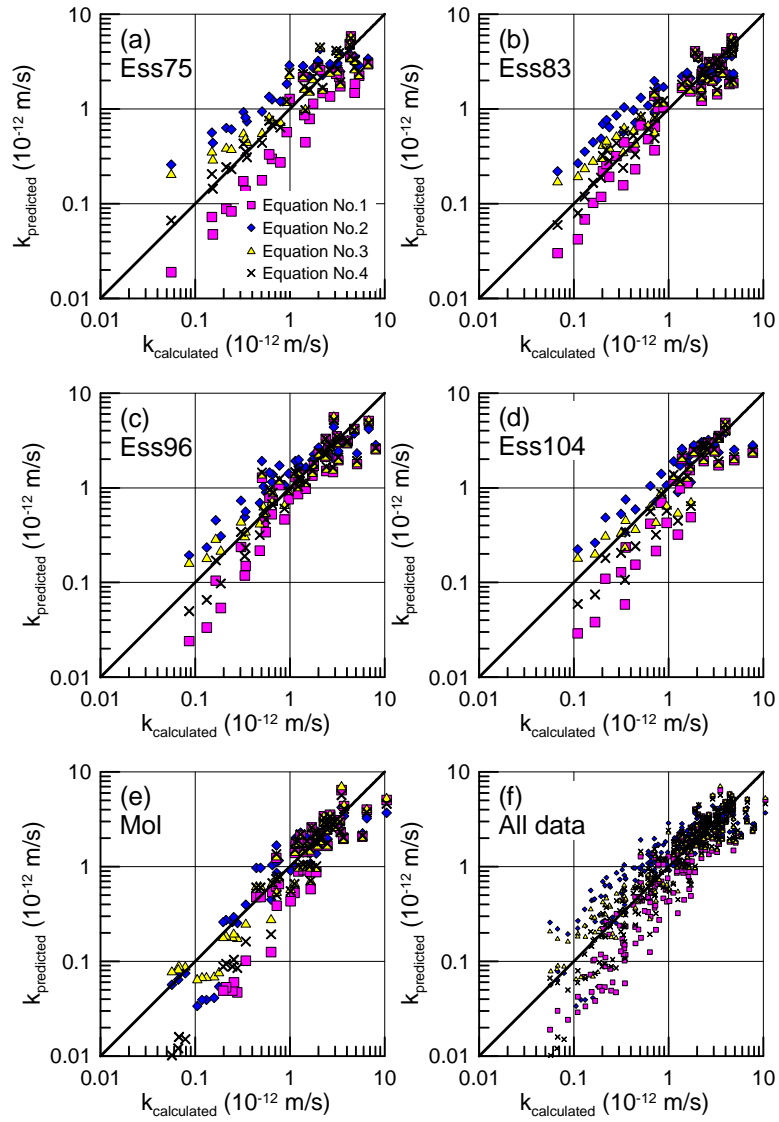
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Figure 6. Relationships between hydraulic conductivity and void ratio; (a) Ess75, (b) Ess83,

3

(c) Ess96, (d) Ess104

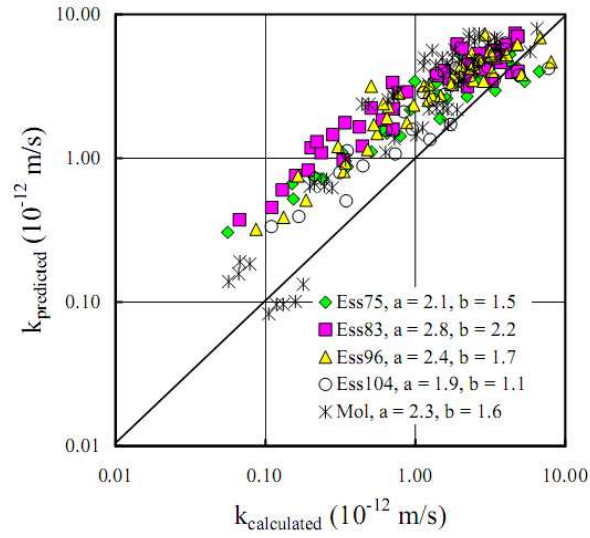


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2 *Figure 7. Predicted hydraulic conductivity versus experimental one – models with known  $k_0$ ;*  
 3 *(a) Ess75, (b) Ess83, (c) Ess96, (d) Ess104, (e) Mol, (f) all data*

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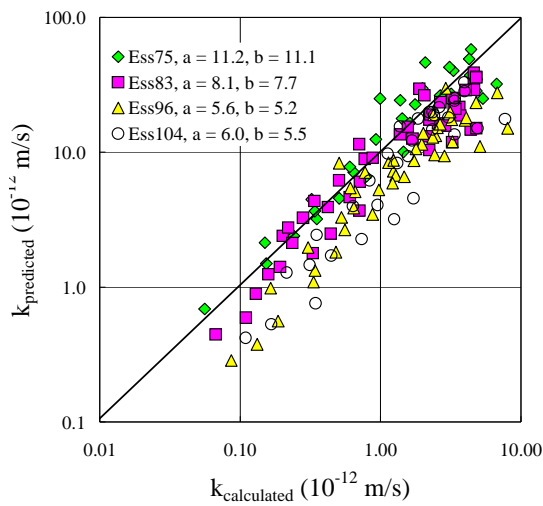




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(a)



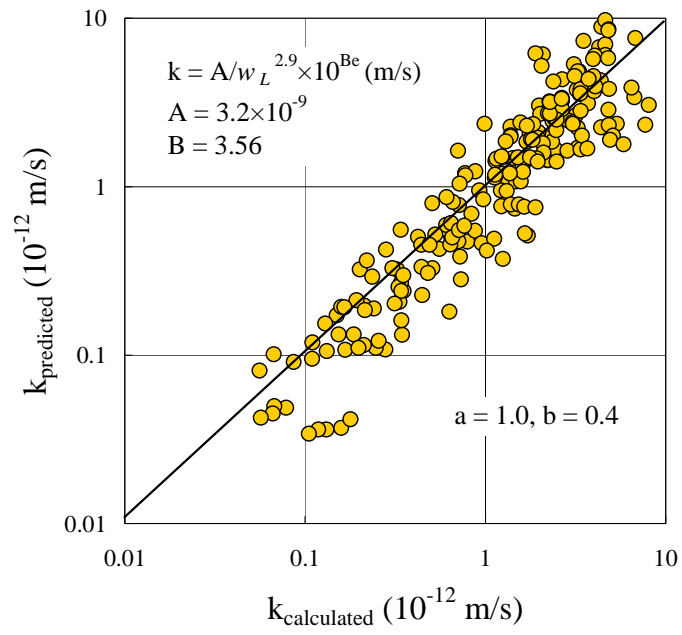
(b)

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4 *Figure 8. Predicted hydraulic conductivity versus experimental one – models without  $k_0$ ; (a)*

5 *Equation No. 2, (b) Equation No. 4*

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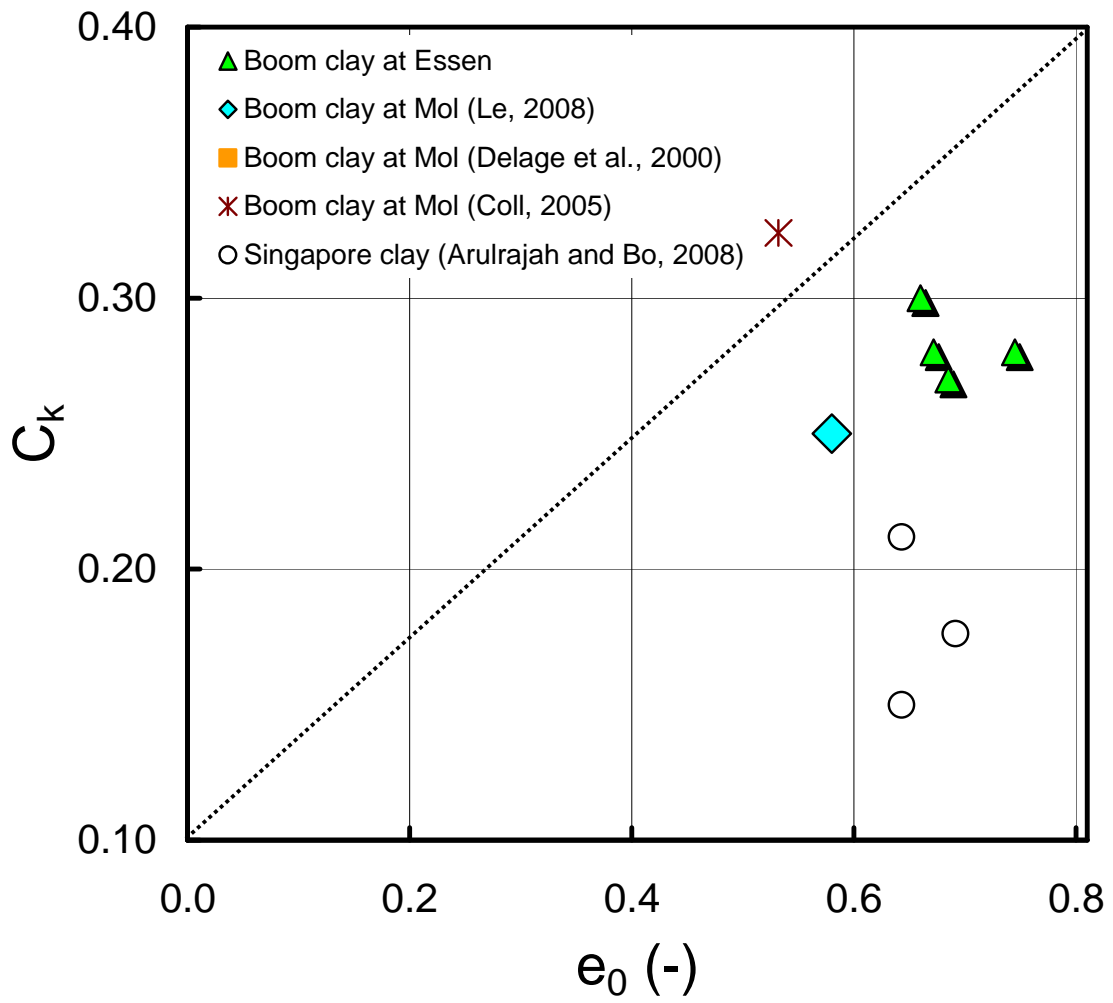


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*Figure 9. Hydraulic conductivity predicted by the proposed correlation versus the experimental one*

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

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