Evaluation of the Hydraulic Conductivity of Clayey Soil Mixed with Calcium-Bentonite Using Odeometer Tests

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ABSTRACT: The hydraulic conductivity of clayey soil/Calcium-bentonite backfills for vertical cutoff wall is evaluated based on a series of oedometer tests. Kaolin is used as the control clayey soil, and the Ca-bentonite content is set at 0, 5%, 10% and 15%. The results reveal that the hydraulic conductivity are significantly affected by the bentonite content, with a hydraulic conductivity that is generally lower than 10^{-9} m/s. Three empirical methods are assessed to predict the hydraulic conductivity based on e and e_L (or w_L). The predicted values of hydraulic conductivity are found to fall in the range of 1/3 to 3 times those evaluated values. However, the equation based on the frameworks of the Kozeny-Carman (KC) equation is shown to estimate the hydraulic conductivity for both the kaolin-bentonite backfills in this study and the sandy soil-bentonite backfills from earlier reported study with reasonable accuracy.

Keywords: Backfill, Bentonite, Cutoff wall, Hydraulic conductivity, Soil-bentonite.

1. INTRODUCTION

Improper waste disposal practices in the past and accidental spills at numerous sites worldwide have resulted in the contamination of the subsurface soils and groundwater with high amounts of heavy metals and organic pollutants (The World Bank 2010; Du et al. 2012, 2013, 2014a, 2014b, 2014c, 2014d and 2014e). Vertical cutoff walls are widely used as in-situ barriers to control the subsurface migration of contaminated groundwater (USEPA 1984; Sharma and Reddy 2004). Soil-bentonite vertical cutoff walls installed with the slurry trenching technology have been applied extensively in the United States, Canada and Japan; while slag-cement-bentonite (SCB) and cement-bentonite (CB) vertical cutoff walls are commonly employed in European countries by the deep soil mixing, trench cutting re-mixing deep (TRD) soil mixing method, and self-hardening slurry methods (Malusis et al. 2009). Soil-bentonite vertical cutoff walls are often preferred because they possess relatively low hydraulic conductivity (typically ranges from 10^{-9} to 10^{-11} m/s) and are generally cost-effective (Sharma and Reddy 2004).

The effects of the fines content (*FC*), bentonite content (*BC*), grain-size of sand, and any other amendment content (e.g. zeolite and activated carbon) on the compressibility and hydraulic conductivity (k) of sandy soil-Na-bentonite (hereinafter referred to sandy SB) and/or sand-clay (SC) backfills have been extensively investigated in previous studies (Yeo et al. 2005; Malusis et al. 2009; Castelbaum and Shackelford 2009, Hong et al. 2011, Fan et al. 2014). The chemical compatibility of various types of soil-bentonite backfills (or mixtures) was also evaluated by measuring the hydraulic conductivity of the backfills when permeated with salt solutions (Thomson and Foose 2005; Mishra et al. 2009; Malusis and McKeehan 2013).

Soil-bentonite backfills generally consist of Na-bentonite, on-site sandy soils, and amendments such as zeolite and activated carbon to provide low hydraulic conductivity and high contaminant sorption capacity (Yeo et al. 2005; Malusis et al. 2009; Hong et al. 2011). However, previous studies have shown that soil-bentonite backfills and Na-bentonite undergo a considerable increase in hydraulic conductivity when they are exposed to salt, heavy metals or organic solutions (Lo and Yang 2001; Thomson and Foose 2005; Mishra et al. 2009; Fan et al. 2013). Moreover, at some sites, especially those found in developing countries such as China and India, high-quality natural Na-bentonite is scarce, but Ca-bentonite is often available as alternative to make up soil-bentonite backfills. Ca-bentonite has a lower sorption capacity and higher hydraulic conductivity relative to Na-bentonite, which is unfavorable to mitigating the transport of contaminants through soil-bentonite vertical cutoff walls as the sorption capacity and hydraulic conductivity are two important factors that control the performance of the soil-bentonite vertical cutoff walls (Du and Hayashi 2006; Du et al. 2009; Malusis et al. 2009; Hong et al. 2011; Fan et al. 2013). Under such circumstances, clay fraction rich soils (e.g., clayey soils) and Ca-bentonite may be used to prepare clayey soil/Ca-bentonite (hereinafter referred to clayey SB) backfills that could possess lower hydraulic conductivity and higher contaminant sorption capacity as compared to the most common sandy SB backfills. It is significant to note that very few studies have systematically investigated the hydraulic conductivity of clayey SB backfills.

In this study, a comprehensive laboratory investigation is undertaken to: (1) investigate hydraulic conductivity of clayey SB backfills via a series of oedometer tests; (2) evaluate how the initial water content and bentonite content affect the hydraulic conductivity of the clayey SB backfills; and, (3) assess empirical relationships to predict the value of k for the clayey SB backfills based on e, e_L (or w_L). The results obtained from this study are useful to facilitate the design and construction of vertical cutoff walls using clayey SB backfill.

2. MATERIALS AND METHODS

2.1 Constituent soils

The clayey SB backfills are prepared using kaolin and Ca-bentonite. Commercial kaolin is used here to simulate a clayey soil because: (1) it is one of the most common minerals found in natural clays (Grim 1968); (2) it has a low organic content, and a consistent and uniform mineralogy (Yukselen-Aksoy and Reddy 2013); and, (3) it has a relatively lower w_L and activity, while hydraulic conductivity for kaolin is nearly 10 to 1000 times higher than that for bentonite in general (Mitchell and Soga 2005). Thus, kaolin is a good control soil for laboratory tests as the base component of the backfills in order to investigate the effects of bentonite content on the compressibility and hydraulic conductivity.

Table 1 shows the physico-chemical properties and mineralogical compositions of the kaolin and bentonite clays used for this study. Based on the Unified Soil Classification System (ASTM 2011a), the kaolin and bentonite clays are classified as low-plasticity clay (CL) and high-plasticity clay (CH), respectively. The grain size distribution of the soils was measured with a Mastersizer Micro (Malvern, UK). The specific gravity (G_s), liquid limit (w_L), plastic limit (w_P) and pH were measured based on ASTM standards individually (ASTM 2007; ASTM 2010a; ASTM 2010b). The specific surface area (SSA) was determined by the Ethylene Glycol Monoethyl Ether method (Cerato and Lutenegger 2002). Based on the x-ray diffraction analysis, the dominant minerals of the kaolin and bentonite clays are kaolinite and montmorillonite, respectively.

2.2 Preparation of clayey SB backfills

The bentonite content of the kaolin-bentonite (KB) backfills was selected to be 5, 10 and 15% (dry weight basis). The bentonite content (*BC*) in the KB backfills is calculated using Eq. 1:

$$BC = \frac{m_{\mathrm{ben}}}{m_{\mathrm{kao}} + m_{\mathrm{ben}}} \tag{1}$$

where m_{kao} and m_{ben} are the mass of kaolin and bentonite in the mixture (on dry mass basis), respectively. This study also assessed and compared the compressibility and hydraulic conductivity of the kaolin specimens to the KB backfills. The values of bentonite content, specific gravity, liquid limit, and plastic limit for the various KB backfills are tabulated in Table 2.

Table 1 Properties and composition of constituent soils used in this study

Property	Constituent soil	
	Kaolin	Bentonite
Specific gravity	2.66	2.73
Clay fraction (%)	25%	33%
Liquid limit (%)	29.1	331.4
Plastic limit (%)	19.5	88.2
Plastic index	12.8	243.2
Classification	CL	CH
Specific surface area (m^2/g)	45.7	378.5
Principal minerals	Kaolinite	Montmorillonite
pH	8.7	10.0

Table 2 Types and properties of kaolin-bentonite (KB) backfills

Type of backfill*	Bentonite content (*BC*)	Specific gravity [a] (G_s)	Liquid limit [b] (w_L, %)	Plastic limit [b] (w_P, %)
B5	5	2.66	43.9	22.9
B10	10	2.67	53.3	25.9
B15	15	2.67	61.7	29.3

[a] Based on ASTM (2010a)
[b] Based on ASTM (2010b)

The KB backfills were prepared by thoroughly mixing a predetermined mass of air-dried kaolin and bentonite clays with a predetermined volume of distilled water for 10 minutes using an electronic mixer. The initial water content (w_0) of the kaolin specimens and KB backfills were designed to be 0.75, 1.00, 1.25, and 1.50 times their corresponding liquid limits to define the influence of the initial water content on the compressibility. This range of initial water content is controlled due to the face that the initial water content of soil-bentonite backfills is controlled by a target slump (-Δ*H*) of 100 – 150 mm to ensure a sufficient workability via slump test, and the ratio of the water content (*w*) satisfying the target slump to w_L ranges from 1.03 to 1.60 and from 1.06 to 1.25 for sandy and clayey SB backfills, respectively (Yeo et al. 2005; Malusis et al. 2009; Hong et al. 2011; Fan et al. 2014). Thus, the range of these designed initial water content values is supposed to cover the water content required to achieve target slump (i.e., -Δ*H* = 100 to 150 mm). Under such circumstances (i.e., relatively high water content), we believe that homogenous mixing of clayey soil with Ca-bentonite in the field could be archived.

A predetermined mass of kaolin or backfill with a known initial water content was placed in a conventional consolidation ring that was 61.8 mm in diameter and 20 mm in height. The entrapped air bubbles were carefully eliminated by tapping the ring and backfill at regular intervals. Then, the specimens were immersed in distilled water for 48 hours to achieve full saturation.

In each case, two identical specimens were prepared under the same conditions with kaolin alone or KB backfill. The symbol "B*i*LL*j*V*k*" denotes a specimen with *BC* of *i*%, initial water content of *j* times the liquid limit and the identical specimen number of *k*th. For instance, the symbols of B0, B5, B10 and B15 represent specimens with bentonite contents of 0, 5, 10 and 15%, respectively. In addition, a third identical specimen was prepared and then sacrificed for the measurement of the initial water content immediately after saturation soaking step. The measured values of w_0, used to calculate the initial void ratio (e_0) for each specimen, as well as w_0/w_L are listed in Table 3.

2.3 Testing methods

The oedometer tests were conducted as per ASTM D 2435 (ASTM 2011b), except that the initial loading on the specimens was kept at 3.125 kPa. This relatively low loading was chosen to avoid squeezing the soil from the gap that exists between the specimen ring and porous disks (Fan et al. 2013; Fan et al. 2014; Hong et al. 2010). The loading was then doubled for each incremental step (a load increment ratio of one) until a maximum loading of 1600 kPa was reached. The duration of each loading was 24 hours.

At a given average effective vertical compression stress (σ'_{ave}), defined as the mean value of two successive load increments, the hydraulic conductivity (*k*) for each load increment was determined following Terzaghi's one-dimensional consolidation theory, as expressed by:

$$k = c_v m_v \gamma_w \tag{2}$$

where *k* is the hydraulic conductivity (m/s), c_v is the coefficient of consolidation (m^2/s) determined using the Taylor (square-root-of-time) method, m_v is the coefficient of volume change (kPa^{-1}), and γ_w is the unit weight of water (kN/m^3). This method to determine hydraulic conductivity is extensively accepted (Sivapullaiah et al. 2000; Chai et al. 2004; Horpibulsuk et al. 2007; Yong et al. 2009, Horpibulsuk et al.2011; Mishra et al. 2011; Watabe et al. 2011). Therefore, it is used to compare and evaluate the relative hydraulic conductivity of the clayey soil-bentonite backfills (Sivapullaiah et al. 2000).

Table 3 Initial water content (w_0) and ratio of water content to liquid limit (w_0/w_L) for kaolin clay and kaolin-bentonite backfills

Specimen dsignation	w_0 (%)	w_0/w_L	Specimen deignation*	w_0 (%)	w_0/w_L
B0LL0.75	20.9	0.72	B0LL1.25	35.3	1.22
B0LL1.00	27.6	0.95	B0LL1.50	45.0	1.55
B5LL0.75V1	31.3	0.71	B5LL1.25V1	53.7	1.22
B5LL0.75V2	31.6	0.72	B5LL1.25V2	53.2	1.21
B5LL1.00V1	43.0	0.98	B5LL1.50V1	63.5	1.45
B5LL1.00V2	41.8	0.95	B5LL1.50V2	64.3	1.46
B10LL0.75V1	37.6	0.70	B10LL1.25V1	65.0	1.22
B10LL0.75V2	38.7	0.73	B10LL1.25V2	64.2	1.20
B10LL1.00V1	51.1	0.96	B10LL1.50V1	78.5	1.47
B10LL1.00V2	52.3	0.98	B10LL1.50V2	77.8	1.46
B15LL0.75V1	47.1	0.76	B15LL1.25V1	78.9	1.28
B15LL0.75V2	46.5	0.75	B15LL1.25V2	77.0	1.25
B15LL1.00V1	62.7	1.02	B15LL1.50V1	94.4	1.53
B15LL1.00V2	62.7	1.02	B15LL1.50V2	92.1	1.49

3. RESULTS AND DISCUSSION

3.1 Compression curves

Figures 1(a) to 1(d) show the void ratio (e) – effective vertical compression stress (σ') compression curves in semi-logarithm scale for the KB backfills and kaolin specimens with w_0 of 0.75 to 1.50 times their corresponding liquid limits. The e-log(σ') compression curves display a noticeable inverse 'S' shape, which is more noticeable for the backfills with a bentonite content of 10 and 15% and a w_0 of 0.75 and 1.0 times their corresponding liquid limits. This inverse 'S' shaped e-log(σ') compression curve and the particular stress (i.e., remolded yield stress, σ'_{yr}) were also observed in the remolded clayey soils with w_0 of approximately 0.5 to 2.0 times

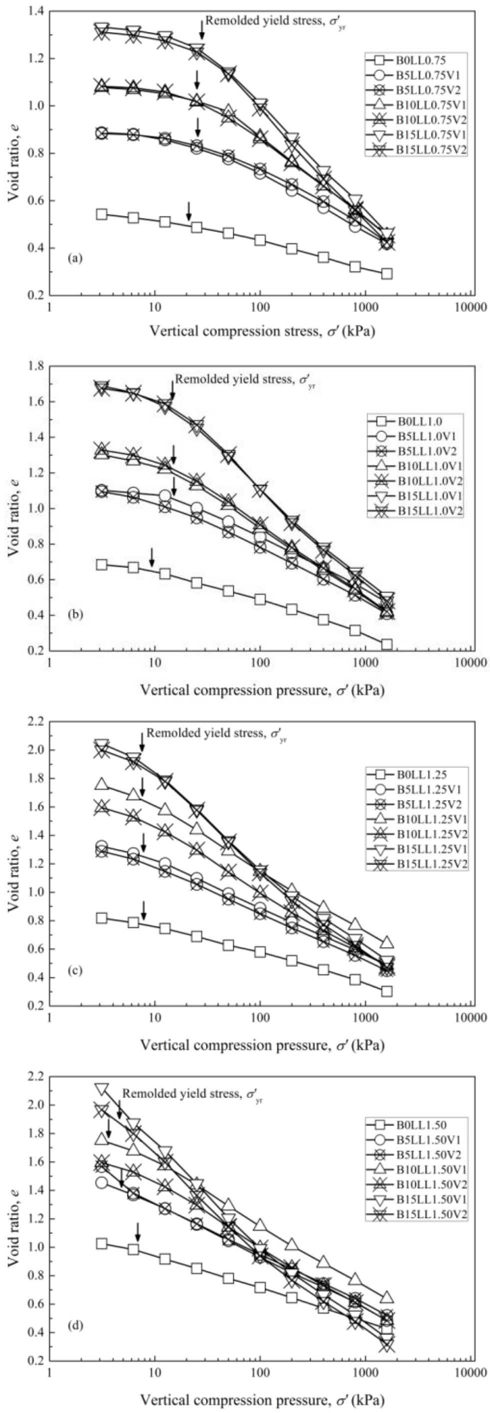

Figure 1 e-log(σ') compression curves of the kaolin-bentonite backfills with various initial water content: (a) $w_0 = 0.75w_L$; (b) $w_0 = 1.0w_L$; (c) $w_0 = 1.25w_L$; and (d) $w_0 = 1.5w_L$

their corresponding liquid limits (Sridharan and Murthy 1986; Hong et al. 2010; Horpibulsuk et al. 2011). The σ'_{yr} in this study is defined as the stress at the intersection point of the linear portions of e-log(σ') compression curve at pre- and post-yield states, as suggested by Hong et al. (2010) for the remolded natural clays. The existence of the σ'_{yr} can be attributed to the fact that the clays are not at fully virgin state and they are able to sustain certain resistance to external compression, as suggested by Hong et al. (2010, 2012).

The variations of C_c with bentonite content (BC) for the KB backfills and kaolin specimens at different w_0 is presented in Figure 2, along with the results of the examinations of the sandy SB and sand-clay backfills reported in previous studies (Baxter 2000; Yeo et al. 2005; Malusis et al. 2009; Hong et al. 2011; Fan et al. 2014). As shown in Figure 6, the C_c value for the KB backfills increases notably as the bentonite content rises: the C_c values range from 0.24 to 0.37, 0.34 to 0.54, and 0.45 to 0.76 for the B5, B10 and B15 backfills, respectively. For the kaolin specimens, C_c ranges from 0.11 to 0.23. In addition, the C_c values of various types of sandy SB backfills reported in earlier studies are slightly lower than those of the KB backfills presented here. This is attributed to a higher C_c value for the kaolin specimen relative to the sandy soil.

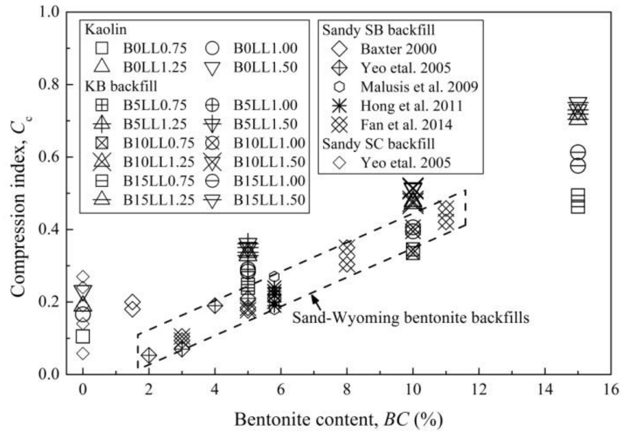

Figure 2 Variations in compression index (C_c) with bentonite content (BC) and for the backfills presented in this study and previous studies

Figures 3 and 4 present the variations in coefficient of consolidation (c_v) as well as coefficient of volume change (m_v), with average effective vertical compression stress on dual-logarithmic scale. The c_v value is evaluated based on the Taylor's (square-root-of-time) methods. The results indicate that the c_v value increases noticeably with an increase in average effective vertical compression stress; while the m_v value tends to considerably decrease with increased average effective vertical compression stress for all the backfills tested in this study. The trend of variations in c_v with σ'_{ave} is similar to the trend obtained from uncontaminated sandy SB backfills (Yeo et al. 2005). In addition, it can be seen from Figure 3 that the c_v value is critically controlled by bentonite; whereas initial water content has marginally influence on c_v. The c_v of kaolin specimens is approximately 5 to 15, 8 to 30, and 10 to 55 times larger than that of B5, B10 and B15 backfills for a given initial water content, respectively. The m_v value increases slight with increased bentonite content; and it considerably increases with an increase in initial water content. These changes in c_v with average vertical effective stress is consistent with those of sandy SB backfills, activated carbon-amended sandy SB backfills as well as zeolite-amended sandy SB backfills reported by previous studies (Yeo et al. 2005; Malusis et al. 2009; Hong et al. 2011). The increase in c_v with an increase in σ'_{ave} is attributed to a greater decrease in m_v with increasing σ'_{ave}, as suggested by Hong et al. (2011).

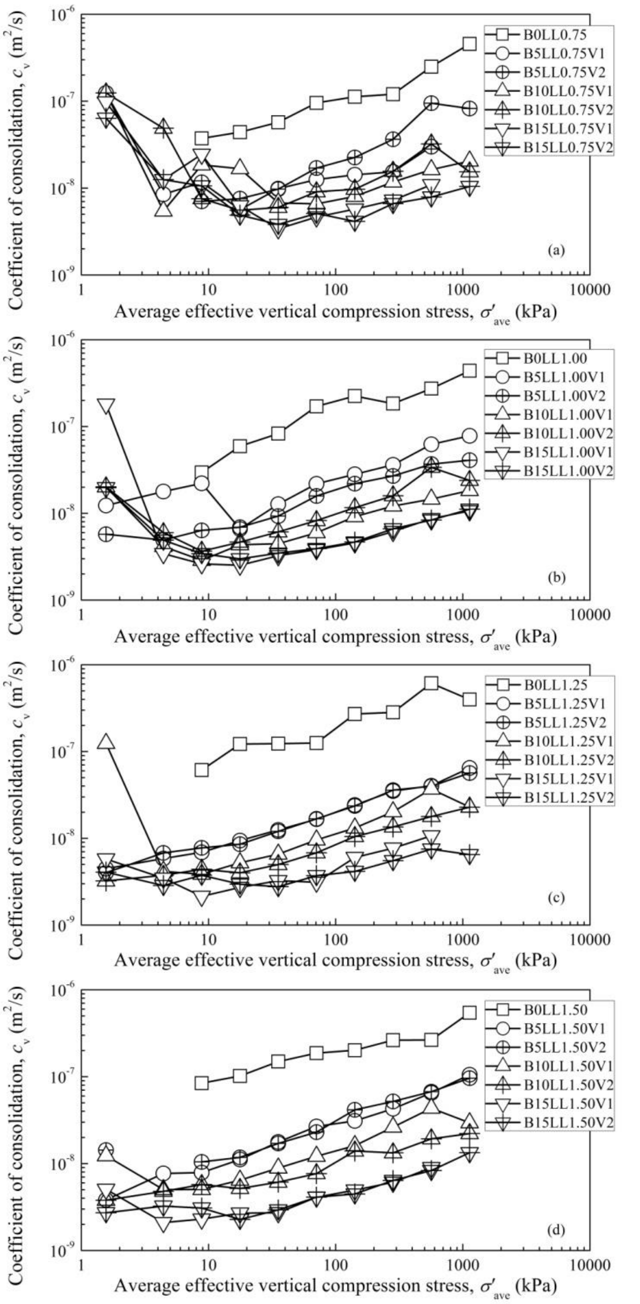

Figure 3 Variations in coefficient of consolidation (c_v) with average effective vertical compression stress (σ'_{ave}): (a) $w_0 = 0.75w_L$; (b) $w_0 = 1.0w_L$; (c) $w_0 = 1.25w_L$; and (d) $w_0 = 1.5w_L$

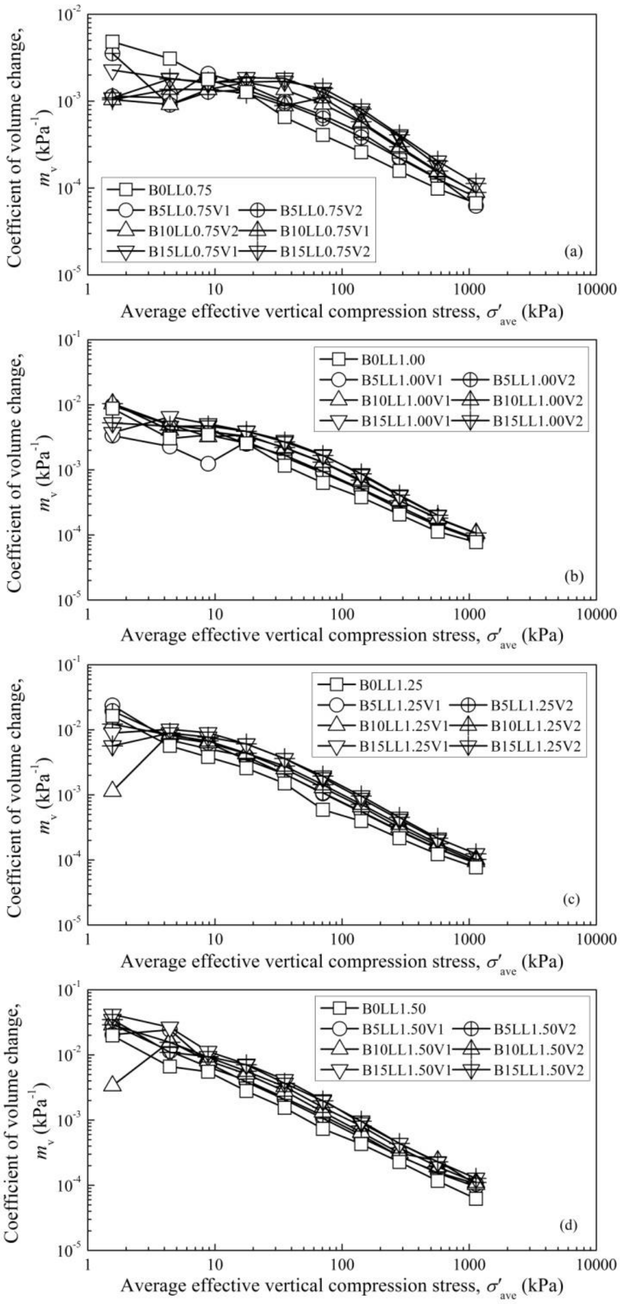

Figure 4 Variations in coefficient of volume change (m_v) with average effective vertical compression stress (σ'_{ave}): (a) $w_0 = 0.75w_L$; (b) $w_0 = 1.0w_L$; (c) $w_0 = 1.25w_L$; and (d) $w_0 = 1.5w_L$

3.2 Hydraulic conductivity

Figure 5 presents the variations of hydraulic conductivity with void ratio in semi-logarithmic scale. It is evident that the *e*-log(*k*) relationship is approximately linear. Most of the *k* values for the KB backfills are lower than 10^{-9} m/s, except for the data at the first two loading increments. In contrast, the *k* values for the kaolin specimens are higher than 10^{-9} m/s when the void ratio higher than a range of 0.4 to 0.6. For a given void ratio, the *k* values for the KB backfills with bentonite contents of 5, 10 and 15% are approximately 15, 25 and 30 times lower than those for the respective kaolin specimens. This is due to the fact that the extent of filling of pore space between clay particles increases with increasing bentonite content. As a result, a relatively tortuous path way for seepage and lower *k* as a consequence yield when the bentonite content increases. In addition, the effect of the initial water content on the *e*-log(*k*) relationship is insignificant regardless of the bentonite content.

Figures 6(a) to 6(b) show the variations in the hydraulic conductivity with bentonite content and the *k-BC* relationship corresponding to $e = 0.8 \pm 0.02$, respectively. The *k* values for the various types of sandy SB and SC backfills reported by Yeo et al. (2005), Malusis et al. (2009), Hong et al. (2011), and Fan et al. (2014) are included for comparison. The results that correspond to a void ratio of 0.8 ± 0.02 are chosen because the hydraulic conductivity values at this void ratio are available from these studies, thus it allows for a comparison between the different backfills. It is evident from Figure 6 that the level of hydraulic conductivity for all types of backfills decreases as the bentonite content increases. However, it should be noticed that the decrease in hydraulic conductivity with that increase in bentonite content is lower for the KB backfills (approximately an order of magnitude decrease) than that observed for the sandy SB backfills. The hydraulic conductivity for the sandy SB backfills decreases with an increase in the bentonite content, with $k = 10^{-5}$ to 10^{-7} m/s at a relatively low bentonite content (BC < 5%) to less than 10^{-9} m/s when the bentonite content is greater than 5%, as indicated by Yeo et al. (2005). At low bentonite content, the hydrated bentonite in sandy SB backfills may not effectively wrap the sand particles, which leads to a relatively lower hydraulic conductivity as compared to that observed when the bentonite content is higher. It should be noted that hydraulic conductivity for the KB backfills containing 5% Ca-bentonite is nearly the same as that of the sandy soil-Wyoming bentonite (i.e., Na-bentonite) backfills reported in previous studies. This leads to the conclusion that the KB backfill (clayey soil/Ca-bentonite backfill) has the potential to be an effective alternative to the conventional sandy SB backfill.

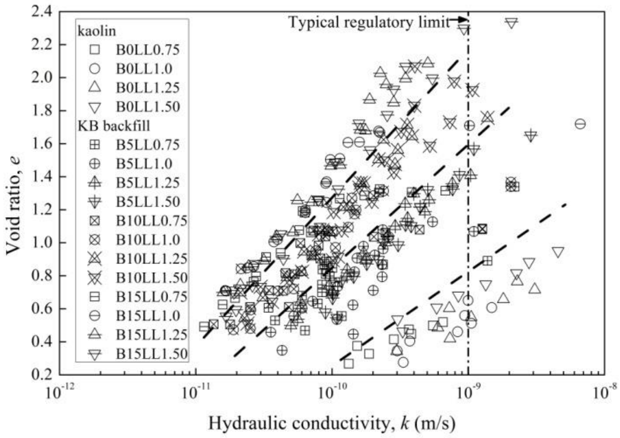

Figure 5 Variations in hydraulic conductivity (k) with void ratio (e) for the backfills presented in this study

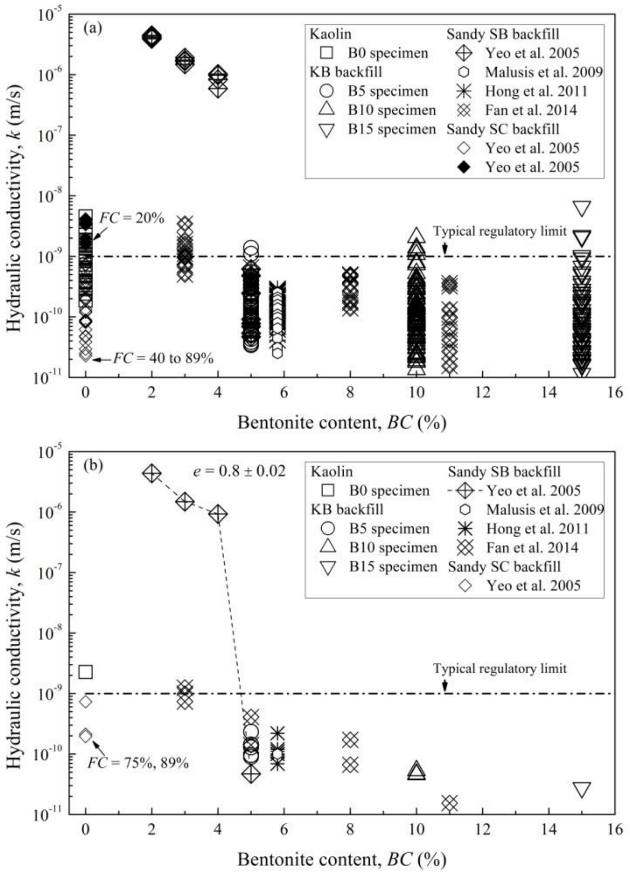

Figure 6 Variations in hydraulic conductivity (k) with bentonite content (BC) for the backfills presented in this study and previous studies: (a) k with various e; (b) k corresponding to $e = 0.8 \pm 0.02$

3.3 Predictive method for *k*

Three empirical equations are assessed to predict the hydraulic conductivity of the KB backfills: (1) Nagaraj's generalized void ratio (e/e_L) method (Nagaraj and Miura 2001), (2) Sivapullaiah et al.'s (2000) method, and (3) proposed method based on the framework of Kozeny-Carman (KC) equation. The Nagaraj method and Sivapullaiah et al.'s (2000) method have been used to predict the hydraulic conductivity of sand-bentonite mixtures with bentonite content that ranges from 5 to 80% (Pandian et al. 1995, Sivapullaiah et al. 2000), while the method based on KC equation can be used to predict k for most saturated soils including sandy soils and natural clays (Chapuis and Aubertin 2003; Sanzeni et al. 2013).

The Nagaraj method for predicting hydraulic conductivity is based on two assumptions: (1) the k for sand-bentonite mixtures is of the same order at the liquid limit state; and (2) the two interacting soil particles are parallel plates. The variations in k values with generalized void ratio can be expressed by (Nagaraj and Miura 2001):

$$\frac{e}{e_L} = a + b\log(k) \tag{3}$$

where a and b are dimensionless parameters representing the intercept and slope of the regressed linear e/e_L-log(k) relationship. Figure 7 presents the relationship between hydraulic conductivity and e/e_L in semi-logarithmic scale. It can be seen that the hydraulic conductivity values for all KB backfills are well generalized using e/e_L, yet the e/e_L-log(k) relationship for the kaolin specimens noticeably deviates from that for the KB backfills. One possible reason for the deviation is the fundamental differences in the behavior of the kaolin and KB mixtures. The kaolin exhibits engineering properties similar to that of a non-swelling soil, whereas the KB mixture displays engineering properties similar to that of swelling soil that consists of the mineral montmorillonite (Sridharan et al. 2007). A regression analysis using the Least-Square-Root method produces Eq. (4) for the KB backfills tested in this study with a fair R value of 0.869, as expressed by:

$$\frac{e}{e_L} = 5.95 + 0.52\log(k) \tag{4}$$

where k is in m/s. It is evident from Figure 7 that Eq. (4) well predicts the hydraulic conductivity for the KB backfills, yet it fails to predict the hydraulic conductivity for the kaolin specimens or the sandy SB backfills as reported by Fan et al. (2014).

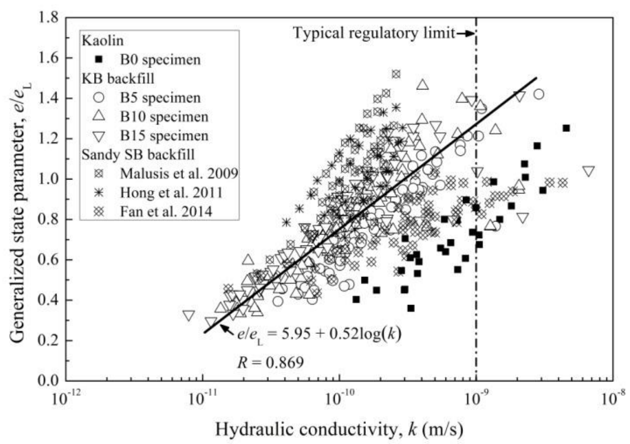

Figure 7 Relationship between hydraulic conductivity (k) and generalized state parameter (e/e_L) in a semi-logarithm scale for the backfills presented in this study

The empirical method suggested by Sivapullaiah et al. (2000) was initially used to predict hydraulic conductivity of sand-bentonite mixtures, and it is based on the observation that the *e*-log(*k*) relationship is represented by a linear function, as expressed by following:

$$e = S_k \log(k) + I_k \tag{5}$$

where the dimensionless parameters S_k and I_k represent the slope and intercept, respectively. Figures 8(a) and 8(b) indicates that both the S_k-w_L and I_k-w_L relationships are approximately linear, as expressed by Eqs. (6) and (7). The high *R* values for Eqs. (6) and (7) are 0.975 and 0.983, respectively. When Eqs. (6) and (7) are substituted in Eq. (5), it yields Eq. (8), which predicts the hydraulic conductivity of both the KB backfills and kaolin specimens used in this study.

$$S_k = 1.8w_L - 0.09 \tag{6}$$

$$I_k = 21.5w_L - 1.76 \tag{7}$$

$$\log(k_p) = \frac{e - 21.5w_L + 1.76}{1.8w_L - 0.09} \tag{8}$$

where w_L is in %, *k*p is the predicted hydraulic conductivity reported in m/s. It is evident from Figure 8 that Eqs. (6) and (7) are not suitable for predicting the hydraulic conductivity for the sandy SB backfills reported by Fan et al. (2014).

The KC equation is commonly used to estimate hydraulic conductivity and it is expressed by:

$$k = C_s \frac{\gamma_w}{\mu_w} \cdot \frac{e^3}{SSA^2(1+e)} \tag{9}$$

where C_s is the shape coefficient that reflects the pore shape and tortuosity of the channels, γ_w is the unit weight of water, μ_w is the dynamic viscosity of water, *SSA* is the specific surface area, and *e* is the void ratio. Chapuis and Aubertin (2003) and Sanzeni et al. (2013) suggested that an inaccurate *SSA* value could lead to a significant discrepancy in the predicted hydraulic conductivity value for clayey soils. As a result, the *SSA* in the original KC equation is replaced by w_L because (1) w_L is a basic soil parameter that is easily determined using conventional soil laboratory testing methods; (2) *SSA* can be estimated from w_L using various relationships (Chapuis and Aubertin 2003); and, (3) *SSA* values for the sandy SB or SC backfills are not available in previous studies including Malusis et al. (2009) and Hong et al. (2011).

Figure 9 presents the relationship between the log(*k*) obtained from the oedometer tests and the dimensionless parameter log[$e^3 \times w_L^{-6}/(1+e)$] for the KB backfills and kaolin specimens. A regression analysis using the Least-Square-Root method gives Eq. (10) with *R* value of 0.872:

$$\log(k) = 1.30\log\left[\frac{e^3}{w_L^6(1+e)}\right] - 11.73 \tag{10}$$

where w_L is in %. An attempt is also made to correlate log[$e^3 \times w_L^{-6}/(1+e)$] to log(*k*) for the KB backfills, kaolin specimens, and sandy SB backfills reported by Fan et al. (2014), and the obtained log[$e^3 \times w_L^{-6}/(1+e)$]-log(*k*) relationship (*R* = 0.859) is expressed by:

$$\log(k) = 1.32\log\left[\frac{e^3}{w_L^6(1+e)}\right] - 11.71 \tag{11}$$

Since Eqs. (10) and (11) are very similar to each other, it is concluded that Eq. (11) is capable of predicting the hydraulic conductivity of the KB backfills, kaolin specimen, and the sandy SB backfills reported by Fan et al. (2014).

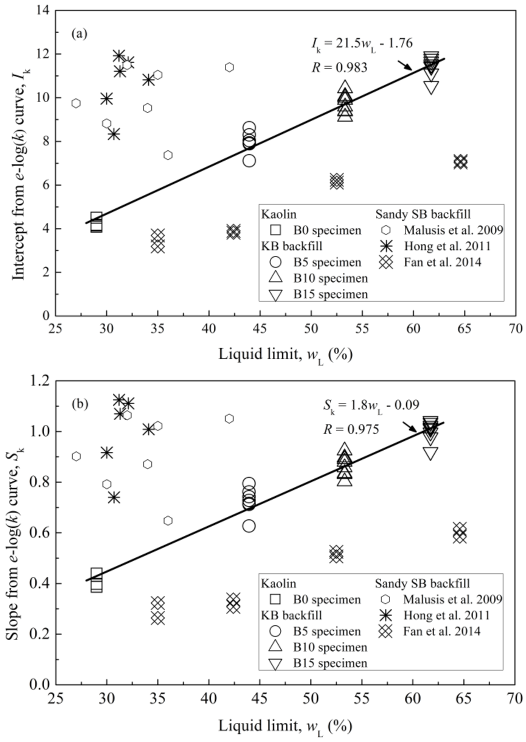

Figure 8 Relationship between liquid limit (w_L) and intercept (I_k) and slope (S_k) form the *e*-log(*k*) relationship expressed using Eq. (8) for the kaolin-bentonite backfills and kaolin clay presented in this study: (a) intercept (I_k); and (b) slope (S_k)

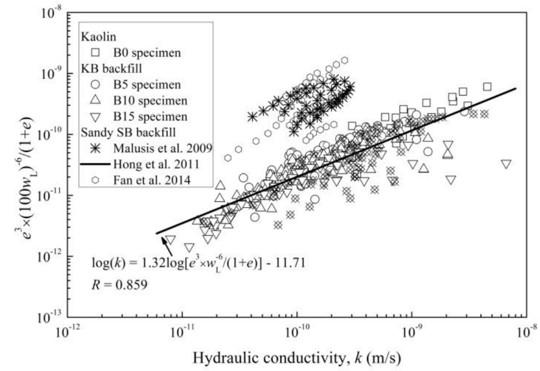

Figure 9 Relationship between hydraulic conductivity (*k*) and $e^3/[w_L^6 \times (1+e)]$ in a logarithm scale for the backfills presented in this study and Fan et al. (2014)

The predicted hydraulic conductivity (k_p) values using Eqs. (4), (8), and (11) are compared with those determined by the oedometer tests, as shown in Figs. 10(a) to 10(c). It can be seen from Figure 10 that the predicted hydraulic conductivity values are generally in the range of 1/3 to 3 times the hydraulic conductivity measured during the oedometer tests, except for the results of the first two loading increments. Therefore, it is concluded that all the three methods (see Eqs. (4), (8), and (11)) are reasonably suitable to predict the hydraulic conductivity value for the KB backfills with bentonite content that ranges from 5 to 15%.

The results reveal that the Nagaraj's generalized void ratio (e/e_L) method provides a concise approach, yet it fails to predict the hydraulic conductivity for the kaolin specimens presented in this study or the sandy SB backfills reported by Fan et al. (2014). Among the three empirical equations, Eq. (11) is better suited to predict the hydraulic conductivity for the KB backfills and kaolin specimens presented in this study as well as the sandy SB backfills reported by Fan et al. (2014). Nevertheless, all three empirical equations fail to predict the hydraulic conductivity for the sandy SB backfills reported by Hong et al. (2011) and Malusis et al. (2009), as shown in Figs. 7 to 9. Further study is needed to investigate a better approach that will accurately predict hydraulic conductivity of not only the KB backfills and kaolin specimens presented in this study, but also the sandy SB backfills reported in previous studies.

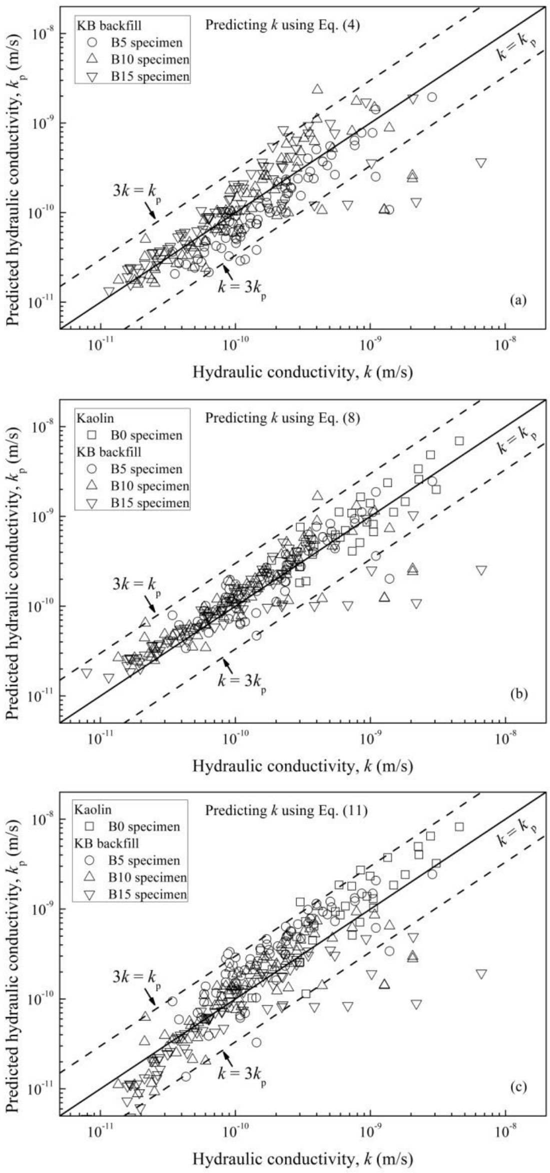

Figure 10 Relationship between the hydraulic conductivity (k) measured from the oedometer tests and the predicted hydraulic conductivity (k_P) using: (a) Eq. 7; (b) Eq. 11; and (c) Eq. 14

4. CONCLUSIONS

Soil backfills that consist of sandy soil and Na-bentonite are commonly used for in-situ barriers to control seepage and contaminant migration. However, such materials may not be easily available in some areas. This study investigates the soil backfills that are prepared using clayey soil and Ca-bentonite (materials that are commonly available in certain areas, especially in developing countries such as China and India). Soil backfills were prepared using kaolin as clayey soil and Ca-bentonite as bentonite and they were evaluated the compressibility and hydraulic conductivity based on a series of oedometer tests. The test results were compared with those for the sandy SB and also limited SC backfills reported in previous studies. The following conclusions can be drawn:

1. The compression curves of the kaolin-bentonite backfills and kaolin specimens exhibited a noticeable inverse 'S' shape that is attributed to the existence of the remolded yield stress (σ'_{yr}). The compression index (C_c) of the KB backfills obtained from this study is relatively higher than that of sandy Sb backfills.
2. The coefficient of consolidation (c_v) and hydraulic conductivity values for the kaolin-bentonite backfills were significantly affected by the bentonite content. Most of the hydraulic conductivity values for the backfills presented in this study are lower than 10^{-9} m/s. The results demonstrate that clayey soil-Ca-bentonite backfills can be applied in the construction of soil-bentonite vertical cutoff walls.
3. Three empirical equations, namely the Nagaraj generalized state parameter (e/e_L) method, Sivapullaiah et al. (2000) method and modified Kozeny–Carman equation, were applied to predict the hydraulic conductivity values for the KB backfills. The results indicate that the predicted hydraulic conductivity values using the proposed equations were within a range of 1/3 to 3 times those obtained from the oedometer tests. The method based on the framework of Kozeny–Carman equation is better suited to estimate the hydraulic conductivity values for both the KB backfills in this study and the sandy SB backfills reported by previous studies.

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NOTATION

a	intercept of regressed linear e/e_L-log(k) relationship
b	slope of regressed linear e/e_L-log(k) relationship
BC	bentonite content
C_c	compression index
C_s	shape coefficient
c_v	coefficient of consolidation
e	void ratio
e_0	initial void ratio
G_s	specific gravity
I_k	intercept of regressed linear e-log(k) relationship
k	hydraulic conductivity
k_P	predicted hydraulic conductivity
m_v	coefficient of volume change
S_k	slope of regressed linear e-log(k) relationship
SSA	specific surface area
w	water content
w_0	initial water content
w_P	plastic limit
w_L	liquid limit
$-\Delta H$	target slump
γ_w	unit weight of water
μ_w	dynamic viscosity of water
σ'	effective vertical compression stress
σ'_{ave}	average effective vertical compression stress
σ'_{yr}	remolded yield stress

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