Seepage Induced Consolidation Model Correlation with Index Properties

M. Janbaz, A. Maher, S. Janbaz

Abstract. Consolidation of soft sediments stored in the confined disposal facilities or mine tailing dams has challenged the scientists to come up with the best consolidation device for the past 50 years. Since the Terzaghi consolidation theory does not apply in soft sediments due to lack of permeability measurements and self-weight effect, the seepage-induced consolidation seems to be the best tool for soft sediments consolidation determination. Besides, index properties are easily obtained in any soil's laboratory and can be fast and accurate. Therefore, correlation of consolidation with index properties can help disposal facility designers to have a better perspective on the consolidation of similar sediments. This paper presents the result of seepage-induced consolidation test on six different soft soils and correlates their index properties with seepage-induced consolidation model. Finally, the correlation results are compared with the test data and similar correlations in the literature. The proposed correlation shows very satisfactory predictions to the laboratory test results.
Keywords: seepage, consolidation, index properties, soft sediments.

1. Introduction

Consolidation of soft sediments has challenged the geotechnical industry for more than five decades. Mine tailings, dredged sediments, and sludges are highly compressible in nature, and they can undergo consolidation under a very small range of stresses. This is an important matter since the available placement areas are decreasing while the production of soft sediments is increasing every day. Low density along with high water content cause self-weight consolidation settlement to be one of the most important parts of consolidation behavior of soft sediments. Due to the time-consuming nature of consolidation, the self-weight effect can significantly influence the design, management, and reclamation of disposal areas.

It is very critical to have a realistic understanding of the consolidation behavior of soft sediments. Consolidation settlement of these materials is important, as they may undergo significant volume change under the influence of relatively small stresses by their own weight or small surcharge. The consolidation process for these soils is highly nonlinear, as the soil compressibility and hydraulic conductivity may change by several orders of magnitude. Field monitoring and laboratory testing of soft sediments have led to significant improvement in their consolidation behavior prediction. Many scientific types of research, such as on Florida Phosphatic soft clays, have been conducted to shed more lights on the consolidation of high water content soft sediments (Abu-Hejleh *et al.*, 1996).

The main problem when dealing with soft sediment consolidation is the lack of competence of the traditional testing procedure. Classical consolidation tests cannot take into account the permeability characteristics of high water content soft sediments. Therefore, since 1979, different testing apparatuses, such as the Constant Rate of Strain Consolidometer (CRSC) by Carrier *et al.* (1983) or the Large Strain Controlled Rate of Strain Consolidation Tester (LSCRSC) by Cargill (1986), have been introduced for accurately predicting the soft sediments consolidation in the laboratory. The most accurate attempt, which overcame the shortcomings of the traditional test setup, *i.e.*, low range of stress, self-weight effect, and permeability measurement, is called seepage-induced consolidation that was introduced by Imai (1979) and later was simplified and improved by Znidarcic & Liu (1989). The advantages of this test method, which can take a week to be completed, are obtaining compressibility and hydraulic conductivity of the slurries in one test and testing under a small range of effective stresses. The minimum effective stress for the traditional test is about 50 kPa while this setup can provide about 0.1 kPa, which is more realistic when dealing with soft sediment self-weight consolidation.

The governing equation of finite strain consolidation of soft sediments, which can include the effect of self-weight and change in permeability and compressibility, was proposed by Gibson *et al.* (1967). Since then, many researchers have tried to introduce a setup that can accurately determine the consolidation behavior of soft sediments (Carrier *et al.*, 1983; Cargill, 1986; and Scott *et al.*, 1986). In some cases, some scientists have tried to propose mathematical approaches in material properties relationships to optimize the solution of the governing equation (Somogyi, 1979; and Cargill, 1983). According to Znidarcic *et al.* (1984), amongst all of the attempts, the proposed setup and

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Submitted on January 31, 2017; Final Acceptance on July 14, 2017; Discussion open until December 29, 2017.

constitutive relationships, *i.e.* void ratio-effective stress (e - σ'), and void ratio-permeability (e - k), by Znidarcic & Liu (1989) provide the best prediction.

The void ratio- compressibility equation was proposed by Liu & Znidarcic (1991) in Eq. 1 as:

$$e = A(\sigma' + Z)^B \tag{1}$$

and the void ratio-permeability equation is proposed by Somogyi (1979) in Eq. 2 as:

$$k = C \times e^D \tag{2}$$

In these equations, e is the void ratio, σ' is the effective stress and k is the hydraulic conductivity. A, B, Z, C, and D are the model parameters which are used to predict the consolidation behavior for all stress levels.

The consolidation behavior model prediction depends on how accurate is the prediction of the model parameters, *i.e.* A, B, Z, C and D. In fact, laboratory test data help to find the model parameters and later the model parameters help to predict the consolidation behavior in the field. The first part of this article discusses the consolidation characteristics of six different clayey soils, prepared in the laboratory, and the second part correlates the index properties of the clays with the consolidation model parameters. Determining these model parameters from index properties can be very useful for the prediction of consolidation behavior of such soils. This can help storage facility designers to have better prediction of consolidation behavior of sediments, required time and settlement magnitude, with simple correlations with the index properties.

2. Materials and Methods

Six types of different soils include soft sediment sampled from Newark bay and five different types of clays which were purchased for the sake of providing different index properties. A total number of six samples were prepared for consolidation test. The Newark Bay sediment was prepared under its natural water content and the clay samples were prepared by adding required water to dry soil to reach 133 percent gravimetric moisture content. According to Estepho (2014), samples with 0.33 to 0.5 solid content, calculated by $\left(\frac{1}{1+w}\right)$, correspond to 100 to 230 percent moisture content (w) and are believed to be moist enough to act as soft sediment, which justified the moisture content of clay samples. The summary of soil and sediment sample tests are presented in Table 1.

2.1. Index properties

Natural water content (w_n), specific gravity of solids (G_s), Atterberg limits (LL, PL, and PI), and hydrometer test will provide the index properties of the soils. The grain size distribution of sediments is presented in Fig. 1.

The summary of index properties test results, including LL as liquid limit (%), PL as plastic limit (%), PI as plasticity index, w_n as natural moisture content (%), LI as liquidity index, G_S as specific gravity of solids and e_0 as initial void ratio in saturated state, is presented in Table 2.

Table 1 - Summary of samples and tests.

Type	Designation	Test type
Bay mud	BM	*Gs* (ASTM D854), Atterberg Limits (ASTM D4318), Natural water content (ASTM D2216), Hydrometer test (ASTM D422), Seepage Induced Consolidation (SICT)
Kaolin Red clay	KR	
Kaolin White clay	KW	
Sea clay	SC	
Moroccon clay	MC	
Rhassoul clay	RC	

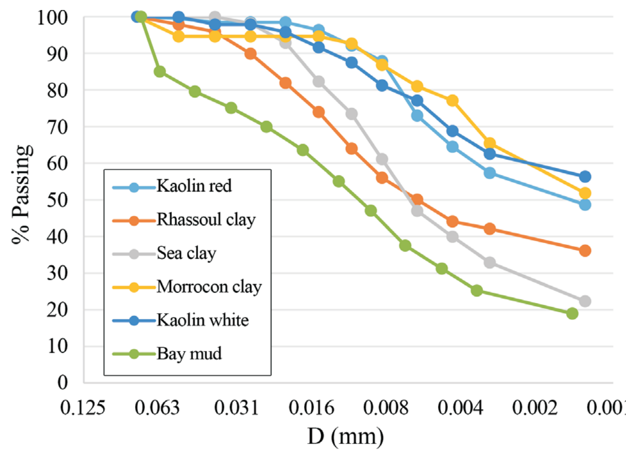

Figure 1 - Grain size distribution.

The range of plasticity index (PI) is 9 to 30, which covers a good range of plasticity indices in the Plasticity chart presented in Fig. 2.

Also, the specific gravity of solids (G_s) is in the range from 2.2 for Newark Bay sediment sample to 2.85 for Moroccon clay. The USCS classification indicates low to high plasticity organic clays.

2.2. Seepage induced consolidation test

The Seepage Induced Consolidation Test (SICT) has been used for over two decades to determine the consolidation characteristics of soft sediments, such as dredged sediments and mine tailings (Abu Hejleh & Znidarcic, 1994; Znidarcic *et al.*, 2011; Berilgen *et al.*, 2006; Pedroni & Aubertin, 2008; and Estepho, 2014). The efficient procedure of this test can result in permeability and compressibility relationships for the soft sediments which later are used to solve the governing equation of consolidation.

The SICT test consists of three stages. Different stages result in different void ratios measured in different stress levels. The first stage is sedimentation column test that provides the void ratio at zero effective stress. For this stage, a big batch of the desired sediment with specific water content was homogenized thoroughly with laboratory

Table 2 - Index properties test results.

	Kaolin Red	Rhassoul clay	Sea clay	Moroccon clay	Kaolin White	Bay mud
LL (%)	50	44	36	53	55	112
PL (%)	36	27	27	23	30	95
PI (%)	14	17	9	30	25	17
USCS Classification	OH	OL	OL	CH	OH	OH
w_n (%)	133	133	133	133	133	275
LI	6.9	6.2	11.8	3.7	4.1	10.6
G_s	2.42	2.6	2.8	2.85	2.7	2.2
e_0	3.21	3.45	3.72	3.79	3.59	6.05

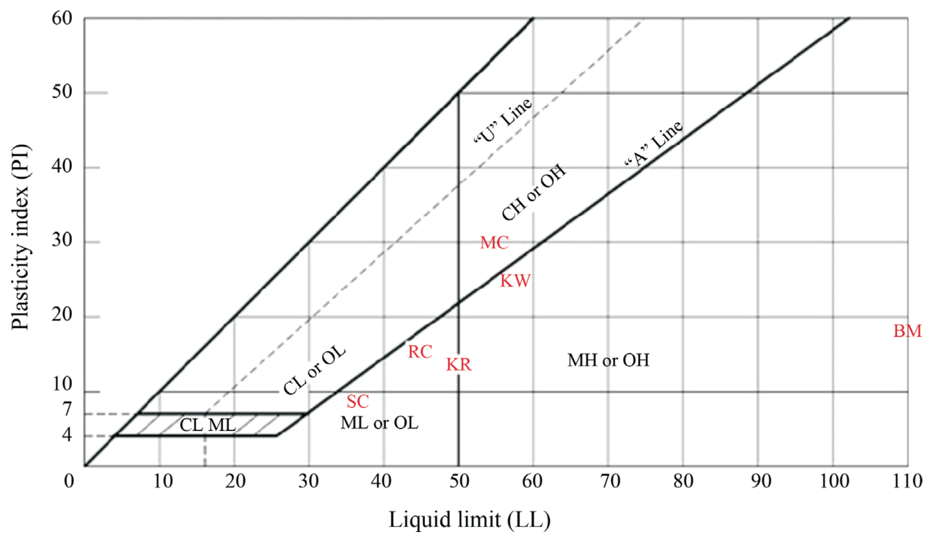

Figure 2 - Plasticity chart (Das, 2013).

mixer and then a representative sample was taken for the sedimentation column test. After homogenizing, the water content of the sample was measured to ensure the accuracy of initial water content. The second stage is consolidation under low effective stresses, created by seepage force and small surcharge (less than 1 kPa), and the last stage is consolidation under the desired surcharge load (10 kPa in this case). There are always intermediate stages, between the second and third stage of the test, based on the magnitude of the stress of interest. The first stage is the sedimentation column which is aside from the actual seepage test apparatus and may take weeks to be completed. Initially, the slurry is poured into a graduated cylinder and is left to settle down under its own weight (Fig. 3).

The average void ratio of the settled material is considered as zero stress void ratio e_0. The second and third stage are performed in the SICT device which is shown schematically in Fig. 4 and result in the two other void ratios for their corresponding effective stresses. The three void ratios are used to find the unknown compressibility model parameters (*A*, *B*, and *Z*) proposed by the Liu & Znidarcic (1991) model. The permeability of the sediment is also measured during the test in all void ratios that can be used to find the other two model parameters (*C* and *D*) proposed by Somogyi (1979).

The setup consists of the water reservoir to provide water to the system, sample chamber, and syringe pump to induce suction and initiate seepage force for consolidating sample. Also, the data acquisition system will record the axial deformation (read by LVDT), seepage rate, stresses and differential pressure between top and bottom of the sample.

3. Results

Figure 5 presents the test results for the six different types of soft sediments in this study. The nonlinear behavior of soft sediments under different effective stresses is presented in (a), while the variation of permeability for different void ratios is depicted in (b).

As expected in soft sediments, the variation of the void ratio in different test stages results in a nonlinear void ratio-effective stress relationship, which proves the incapa-

Figure 3 - Sedimentation column (RC).

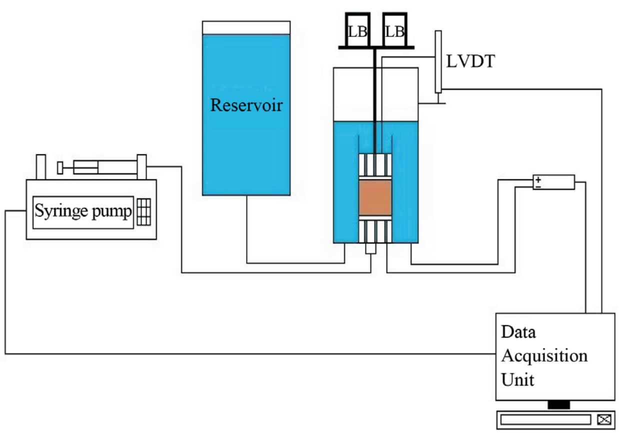

Figure 4 - Seepage induced consolidation apparatus.

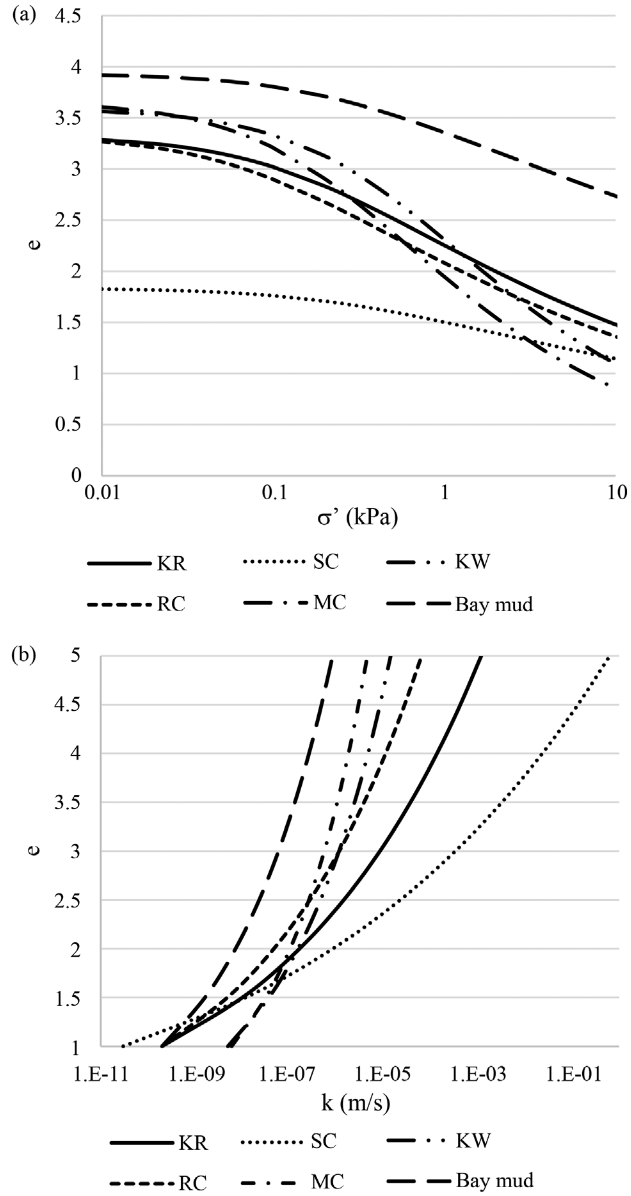

Figure 5 - (a) Effective stress-void ratio (b) void ratio-permeability.

bility of traditional consolidation testing in dealing with soft sediments. Furthermore, the proposed test setup can fully account for inducing small effective stresses on the soil sample which is a crucial part of the consolidation behavior of soft sediments.

The graphs in Fig. 5 present the consolidation model estimation from the test results. Figure 6 shows the actual test measurements for Red Kaolin Clay along with the fitted consolidation model.

Figure 6 shows that the precision of consolidation model estimation is satisfactory. In fact, in order to apply the consolidation model for effective stress void ratio with three unknowns (A, B and Z), three sets of test measurements are enough and the rest of the measured data are redundant, but all of the measurements are presented in Figs. 7 and 8 to ensure the accuracy of model predictions.

3.1. Prediction of model parameters with index properties

It is very practical to determine the model parameters (A, B, Z, C and D) from empirical relationships with index properties. Obtaining index properties is simple and fast while running a complete consolidation test for a soft sediment may take up to ten days. Soft sediment consolidation starts with very small effective stresses that are mostly induced by applying small hydraulic gradient between the two sides of the sample and will take a couple of days, depending on the permeability characteristics of the sediment to come into equilibrium. On the other hand, the index

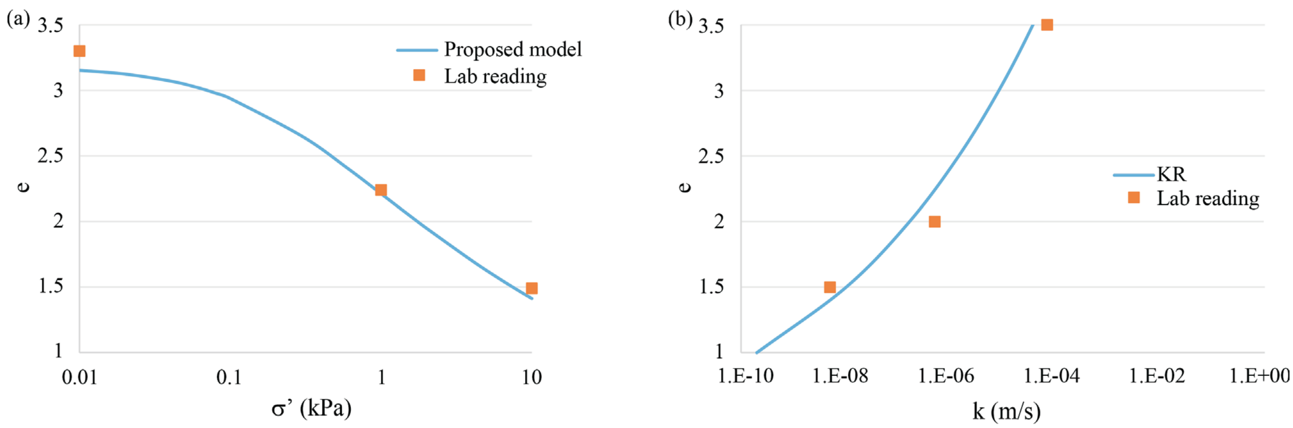

Figure 6 - Test data on Red Kaolin Clay (a) effective stress-void ratio (b) void ratio-permeability.

properties are straightforward and available in any soil's laboratory.

Berilgen *et al.* (2006), proposed their empirical relationships for the seepage-induced consolidation model based on their test results on three different clayey soils and used various published test results to verify their proposition. Based on their findings, the consolidation model parameters, *i.e.*, *A*, *B*, *Z*, *C* and *D* can be correlated with Atterberg limits, liquidity index, and initial void ratio. Table 3 shows their proposed equations for the correlation between abovementioned indices and consolidation model parameters.

In this study also the results of consolidation tests on different samples are statistically correlated with their index properties. The following equations (Eqs. 3 to 7) are presented for consolidation model parameters correlations. The best correlation is achieved based on statistical analysis and is optimized based on the regression coefficient (R^2) of the estimated results *vs.* actual test results.

Table 3 - Correlation equations proposed by Berilgen *et al.* (2006).

Compressibility Model	$A^* = 2.6 \times \exp(0.008 \times PI)$
	$B^* = (1 + e_0) \times [(0.008 \ln(PI)) - 0.054]$
	$Z^* = \exp(-5.51 - (4 \times \ln PI))$
Permeability Model	$C^* = (1 + e_0) \times \exp[1.97 - (3.91 \ln(LI))]$
	$D^* = 7.52 \times \exp[-(0.25 \times LI)]$

Table 4 - Model parameters predictions.

		KR	RC	Bay mud	MC	KW	Bay mud
Test data	A	2.31	2.11	1.55	2.12	2.65	3.42
	B	-0.19	-0.19	-0.13	-0.39	-0.37	-0.097
	Z	0.156	0.093	0.274	0.246	0.451	0.242
	C	2E-10	3E-10	6E-10	5E-10	3E-10	4E-17
	D	9.69	7.63	13.63	4.20	5.36	18.20
Model data	A'	2.30	2.28	1.52	2.27	2.40	3.26
	B'	-0.21	-0.24	-0.12	-0.39	-0.34	-0.14
	Z'	0.216	0.229	0.250	0.316	0.279	0.212
	C'	1.21E-09	2.66E-09	1.37E-09	2.97E-10	9.45E-10	1.03E-16
	D'	9.42	7.92	14.96	4.51	5.36	20.65
Berilgen Model	A*	3.00	3.07	2.88	3.41	3.27	3.07
	B*	-0.142	-0.140	-0.172	-0.128	-0.130	-0.221
	Z*	0.016	0.025	0.002	0.216	0.132	0.005
	C*	1.05E-07	4.84E-08	6.17E-07	5.00E-09	1.04E-08	4.84E-08
	D*	1.33	1.58	0.40	3.01	2.68	0.53

$$A' = \frac{2}{G_s}\log_{G_s} PI \quad (3)$$

$$B' = -\frac{PI}{20 \times e_0} \quad (4)$$

$$Z' = \frac{1}{\log_{G_s} PI \times \log_{e_0} LI} \quad (5)$$

$$C' = \frac{1}{G_s \times PI \times (W_n^{e_0})} \quad (6)$$

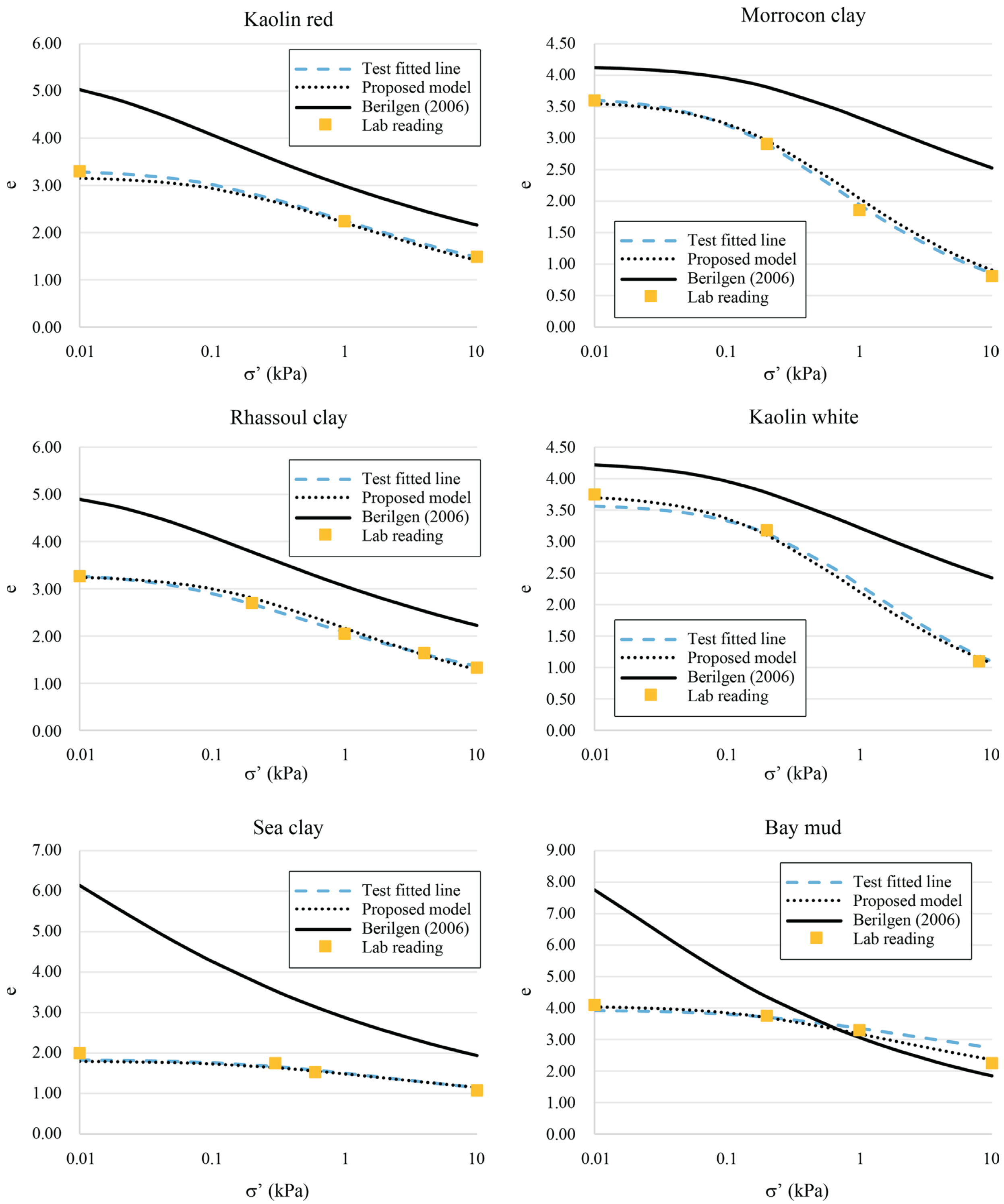

Figure 7 - Comparing test data with two correlating models (compressibility).

$$D' = LI \times \left(1 + \frac{PL}{100}\right) \tag{7}$$

It should be noted that the moisture content in the equations should be in percentage format rather than decimal, *i.e.* 133 should be used instead of 1.33 for 133% mois-

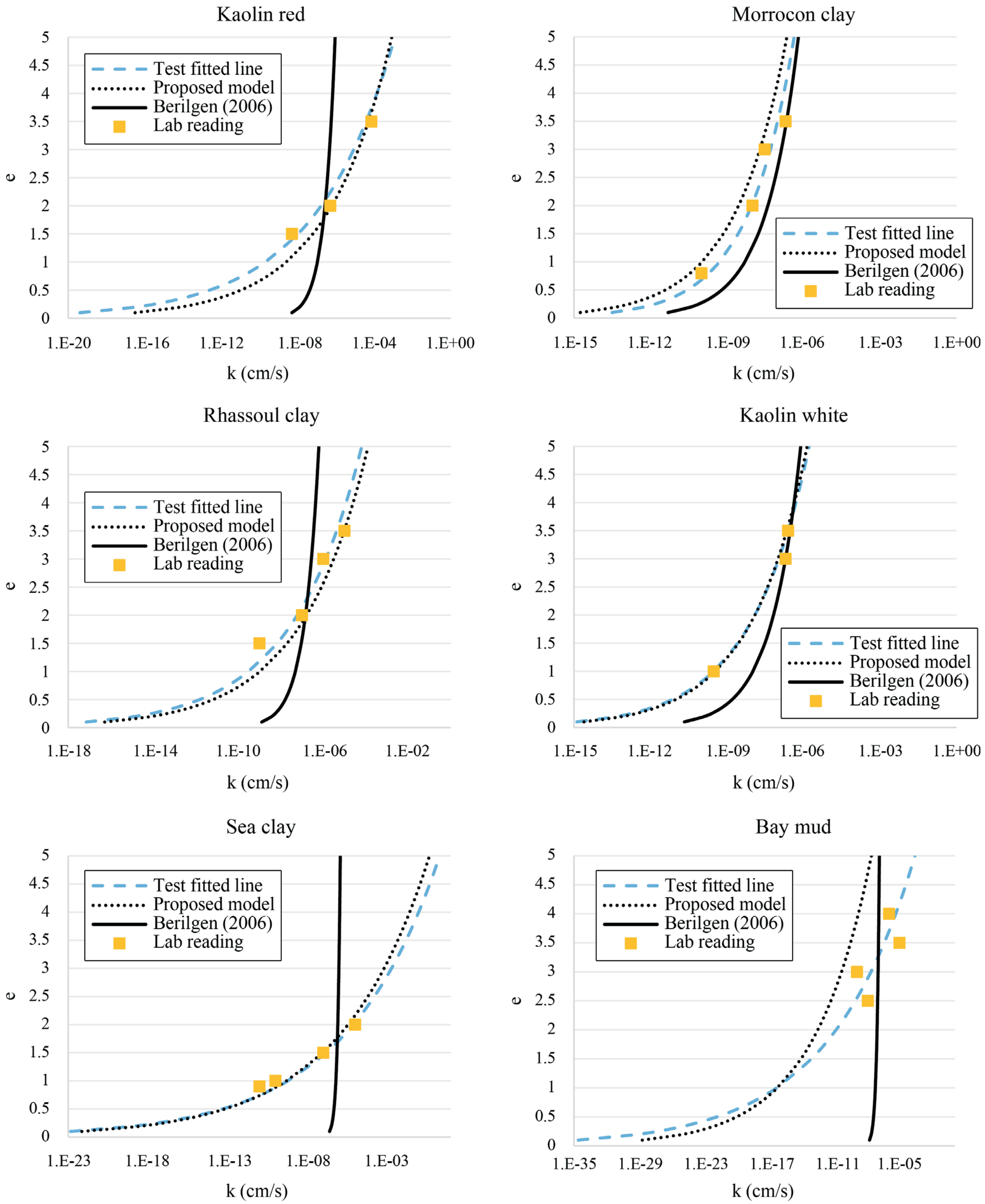

Figure 8 - Comparing test data with two correlating models (permeability).

ture content. The predictions' results are presented in Table 4 for a different type of sediments. Table 4 presents the results of test data from six seepage-induced consolidation tests, model data obtained from the proposed equations and Berilgen *et al.* (2006) correlation equations to compare with the proposed equations.

Figure 7 presents the graphical comparison between these three sets of data, *i.e.* test data, proposed correlation and Berilgen *et al.* (2006) correlation for compressibility equation and Fig. 8 presents the comparison of permeability data.

Figure 7 presents the test results for compressibility of the sediments and it proves that the soft sediments have very nonlinear behavior in a small range of effective stresses. The traditional consolidation test starts the effective stress at 50 kPa while most of the soft sediments undergo the majority of their consolidation in much smaller ranges of effective stresses compared to usual consolidation tests. Figure 8 also presents the nonlinear behavior of soft sediments in permeability measurements. The magnitude of permeability can change significantly with the void ratio in soft soil consolidation, which is neglected in infinitesimal strain consolidation theory. Both Figs. 7 and 8 represent the comparison between proposed equations and test results. This study's proposed correlations show satisfactory results compared to Berilgen *et al.* (2006) proposed correlations. Although the proposed correlations include more index properties in relatively complex format, the resulting approximation is very satisfactory.

4. Conclusions

The results of six seepage-induced consolidation tests are presented in this paper and the correlation between index properties and consolidation model parameters is investigated. Since obtaining the index properties is relatively quick and straightforward, the correlation between index properties and consolidation model parameters for soft sediments could help engineers to come up with good estimates about consolidation behavior of sediments in practice without performing the actual consolidation tests. However, it should be noted that using the correlation should not substitute the laboratory testing. The correlation can be used for initial estimation of consolidation of soft sediment retention ponds and the validity of them should be confirmed by performing an adequate number of laboratory consolidation tests for any specific case. The proposed correlations are compared with published correlations by Berilgen *et al.* (2006) and the results show better compatibility with proposed correlations when compared to Berilgen *et al.* (2006) correlation for the proposed six clays. The correlations proposed herein have a very good agreement with test results and can be used for similar sediments with similar index properties.

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