

Development of new models to predict the compressibility parameters of alluvial soils

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Abstract. Alluvial soil is challenging to work with due to its high compressibility. Thus, consolidation settlement of this type of soil should be accurately estimated. Accurate estimation of the consolidation settlement of alluvial soil requires accurate prediction of compressibility parameters. Geotechnical engineers usually use empirical correlations to estimate these compressibility parameters. However, no attempts have been made to develop correlations to estimate compressibility parameters of alluvial soil. Thus, this paper aims to develop new models to predict the compression and recompression indices (C_c and C_r) of alluvial soils. As part of the study, geotechnical laboratory tests have been conducted on large number of undisturbed samples of local alluvial soil. The obtained results from these tests in addition to available results from the literature from different parts in the world have been compiled to form the database of this study. This database is then employed to examine the accuracy of the available empirical correlations of the compressibility parameters and to develop the new models to estimate the compressibility parameters using the nonlinear regression analysis. The accuracy of the new models has been assessed using mean absolute error, root mean square error, mean, percentage of predictions with error range of $\pm 20\%$, percentage of predictions with error range of $\pm 30\%$, and coefficient of determination. It was found that the new models outperform the available correlations. Thus, these models can be used by geotechnical engineers with more confidence to predict C_c and C_r .

Keywords: alluvial soil, compression index, mean absolute error, nonlinear regression, recompression index, root mean square error

1. Introduction

In terms of stress-strain and time-dependent behavior, the soil is considered as one of the exceedingly complicated geomaterials. This is due to many issues like the time-dependent response to loading, elastoplastic behavior in both loading and unloading conditions, non-linear stress-strain relationships, and effect of stress history (Budhu 2007, Holtz *et al.* 2011, MolaAbasi *et al.* 2016). In addition, the behavior of the soil is highly influenced by factors associated with geological, hydrogeological, and climatic circumstances (Breyse *et al.* 2005, Chrétien *et al.* 2007, Masoud 2016). It is, therefore, imperative to understand major aspects and potential problems of soils (especially, soil's settlement) early on during the preliminary design stage to ensure that proper design strategy is chosen for the foundation.

The time-dependent consolidation settlement is one of the major aspects in the design as its effect becomes visible in the long term (Budhu 2007, Holtz *et al.* 2011, MolaAbasi *et al.* 2016). Consolidation parameters (compression index (C_c) and recompression index (C_r)) are used to calculate the

consolidation settlement. These parameters are obtained from the consolidation test, or they may be predicted indirectly from other simple tests using empirical correlations (Kulhawy and Mayne 1990, Albusoda and Al-Taie 2010, Alkroosh *et al.* 2020).

The compression indices (C_c and C_r) are obtained from the consolidation test by plotting the relationship of the void ratio (e) and the log of the applied pressure. The laboratory consolidation test takes a long time and requires a lot of efforts. In any way, it is somewhat costly, and in most circumstances at least two (and ideally three) tests in each crucial stratum should be undertaken. Because of these reasons, a significant research effort has been made to try to relate C_c and C_r empirically to other soil index characteristics that can be found more easily and in lower cost (Bowles 1996, Al-Taie *et al.* 2017).

The consolidation parameters of the soils are influenced mainly by state parameters such as natural water content and initial void ratio (Kurnaz *et al.* 2016). According to Terzaghi (1996), a direct relationship between C_c and natural water content of soil should exist, both of these properties are controlled by composition and structure (Terzaghi 1996, McCabe *et al.* 2014). On the other hand, Bowles (1996), Kurnaz *et al.* (2016) and Al-Khafaji *et al.* (2017) discussed the need to incorporate e_o , either directly or indirectly, to estimate the compressibility parameters empirically because the initial in situ void ratio (e_o) affects compression settlement. These discussions/observations

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encouraged many researchers to develop empirical correlations to predict compressibility parameters of fine-grained soils. Koppula (1981) developed a correlation to predict the compression index of fine-grained soils using the initial water content. Al- Khafaji and Andersland (1992) correlated the compression index of fine-grained soils with the void ratio and the liquid limit. Ozer *et al.* (2008) assessed the empirical correlations that are available in the literature to predict the compression index of fine-grained soils. They also developed new linear and non-linear correlations to predict the compression index using regression analysis. They also compared the accuracy performance of the regression analysis with the artificial neural network (ANN) and found that the ANN offered better accuracy. Vinod and Bindu (2010) studied the accuracy of the available empirical correlations of the compression index utilizing results of high plastic clay of Kuttanad region in India. They concluded that the available correlations did not provide good prediction of the compression index for the clays of the Kuttanad region. They also developed new site-specific model to predict the compression index. Park and Lee (2011) developed black box ANN model to predict the compression index of fine-grained soils of Korea. They also compared the accuracy of the predictions of the new model with the available correlations and found that the new model provided better accuracy. Mohammadzadeh *et al.* (2014, 2016) developed soft computing models to compute the compression index of fine-grained soils using different soft computing algorithms. In addition, Güllü *et al.* (2018) and Alkroosh *et al.* (2020) noticed poor performance of the available correlations of the compression index for the case fine-grained soils in middle and south of Iraq. They also stated the need to develop correlations with better accuracy. Alzabeebee *et al.* (2021a) utilized evolutionary polynomial regression analysis (EPR-MOGA) to develop correlations to predict the compression index of fine-grained soils of Sulaymaniyah province in north of Iraq. Alzabeebee *et al.* (2021b) employed EPR-MOGA to propose soft computing models to predict the recompression index of fine-grained soils of Baghdad and Sulaymaniyah provinces in Iraq. They also compared accuracy of the EPR-MOGA models with those available in the literature and found that the new models outperformed other available correlations.

Based on this review, it is evident that there is no study that examined the accuracy of the available correlations for the case of alluvial soils considering a global database. In addition, there are no attempts to develop new correlations to predict the compressibility parameters of alluvial soils considering global database, where most of the studies used site specific soils in the development of the empirical correlations of the compressibility parameters. Thus, it is very important to examine and enhance the empirical predictions of the compressibility parameters of the alluvial soils so that design engineers could use the empirical approach in the assessment of the consolidation settlement with higher confidence. Therefore, this paper aims to achieve this goal so that geotechnical engineers could have better correlations to predict the compressibility parameters.

It is worthy to state that this paper involves experimental

work, data collection, regression analysis, and statistical accuracy examination. Section 2 provides a brief review of alluvial soils, while Section 3 explains the methodology of the study. Section 4 discusses the development of the database of the study. In addition, Sections 5 and 6 discuss the development of the compression index and recompression index new models, respectively. Finally, Section 7 summarizes the main findings of the study.

2. Alluvial soils

Soils from the Quaternary period are the most frequent geological materials found at or near the surface of the Earth. The majority of alluvium is Quaternary in age and is referred to as “cover” because it obscures the underlying bedrock. The majority of non-lithified sedimentary material that fills a basin (“basin fill”) is referred to as “alluvial” (Chisholm 1911, Culshaw *et al.* 1991). The term “alluvium” refers to all kinds of loose sediments deposited by running water in alluvial fans, floodplains, and associated landforms, (Jakson 1997, Miller and Juilleret 2020).

Geotechnical engineers are particularly interested in Quaternary alluvial soils because of their surface occurrence where numerous engineering buildings have been built in or on these soils. Many of the world's cities are built on Quaternary soils, which provide the foundation material for part or all of them. Previously, alluvial soils were thought to be continuous bodies of clayey-silty and occasionally sandy deposits. Rather, the formations were discovered to be mostly heterogeneous and comprised of a variety of facies (Kiersch 1995, Campolunghi *et al.* 2007, Khan *et al.* 2022).

Unfortunately, alluvial soils are challenging to utilize as foundation materials, they are compressible and low-bearing material (Culshaw *et al.* 1991, Al-Taie *et al.* 2021, Khan *et al.* 2022). Due to these poor characteristics, many of the buildings situated on alluvial soils underwent uniform or differential settlement, and therefore, they were damaged (Campolunghi *et al.* 2007). Yilmaz and Karacan (2002) stated that the alluvial soil from Erbaa Basin, Turkey, may undergo significant settlement under loads that exceed the preconsolidation pressure of the soil. Raspa *et al.* (2008) indicated that alluvial soils which cover a large important portion of Roma city, Italy, and be the foundation for many historic neighborhoods, monuments, and archaeological areas are vulnerable to high levels of a geohazard. Alluvial soil from different localities along Sanaga-River, Center Cameroon, exhibited some engineering problems represented by high volume change under drying conditions (Nzeukou *et al.* 2013). Eskişar *et al.* (2014) found that under loading condition, the thick loose alluvial soils in İzmir Bay, Turkey, undergo large settlement (from one-dimensional methodology). May *et al.* (2015) reported that the Quaternary alluvial muddy soils of Tunis city, Tunisia, have weak geotechnical properties and produce different settlement risks. Masoud (2015) analyzed the extensive geotechnical data of alluvial soils in Egypt's Gharbiya governorate. According to his analysis, one of the dominant geotechnical problems of the studied alluvial soils is their

compressibility potentials.

There are real challenges that geotechnical engineers may face as a result of the compressibility of alluvial soils. Thus, it is necessary to assess the settlement characterization of alluvial soils. Thus, developing new accurate models to predict the settlement parameters of alluvial soils is necessary. Such models can be used for the preliminary estimates of settlement in areas of alluvial soils before conducting site investigation and soil testing for the final design.

3. Methodology

This study consists of experimental and theoretical stages. Initially, a large number of undisturbed samples of local alluvial soils have been obtained from sites in southern of Iraq. Then, laboratory tests have been carried out to obtain the basic and consolidation properties of the collected samples. In the theoretical stage, databases of geotechnical properties have been developed for investigated local test results as well as for alluvial soils from different locations in the world. Then, the accuracy of the available empirical correlations of the compressibility parameters has been assessed. Accordingly, the nonlinear regression analysis has been employed to develop new and more accurate models. The accuracy of the available and new models has been assessed using mean absolute error, root mean square error, mean, percentage of predictions with error range of $\pm 20\%$, percentage of predictions with error range of $\pm 30\%$, and coefficient of determination (R^2). Thus, the methodology of the analysis involves three steps as follows:

1. Develop comprehensive databases of the compression and recompression indices to facilitate the development of the new models and to assess the accuracy of the available empirical correlations. The development of the database involves experimental work and data collection from the literature as will be elaborated further in the manuscript.
2. Develop new models to predict the compression and recompression indices. The nonlinear regression analysis has been employed in the development of the new models. This method has been considered a robust choice because only one variable is involved in the correlation (Terzaghi 1996, McCabe *et al.* 2014, Kurnaz *et al.* 2016, Al-Khafaji *et al.* 2017).
3. Assess the accuracy of the new models and compare the accuracy of these models with the available correlations. The assessment is based on calculating statistical accuracy indicators. As suggested in previous studies, these indicators are the mean absolute error (MAE), root mean square error (RMSE), Mean, percentage of predictions within error range of $\pm 20\%$ (P20), percentage of predictions within error range of $\pm 30\%$ (P30), and R^2 . The equations employed in the calculations of these indicators are shown in Equations 1 to 6 (Alkroosh *et al.* 2020, Zhang *et al.* 2020, Alzabeebee 2022a, b, Alzabeebee *et al.* 2021, Eskisar 2021, Alzabeebee *et al.* 2022a, b, Armaghani *et al.* 2021, Bai *et al.* 2021, Luat *et al.* 2020a, b, Zhang *et al.* 2020,

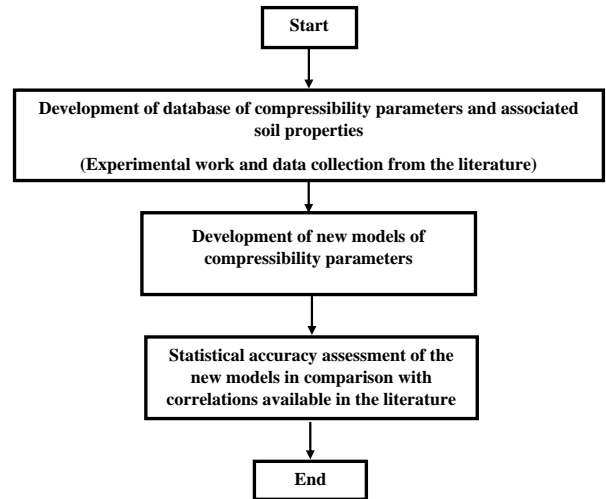


Fig. 1 Flow chart of the methodology of this study

2021a, b, Zuhaira *et al.* 2021).

$$MAE = \frac{1}{n} \sum_{i=1}^n |Cc \text{ or } Cr_{(p)} - Cc \text{ or } Cr_{(m)}| \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Cc \text{ or } Cr_{(p)} - Cc \text{ or } Cr_{(m)})^2} \quad (2)$$

$$Mean = \frac{1}{n} \sum_{i=1}^n \left(\frac{Cc \text{ or } Cr_{(p)}}{Cc \text{ or } Cr_{(m)}} \right) \quad (3)$$

$$P20 = \frac{Sum20}{n} \times 100 \quad (4)$$

$$P30 = \frac{Sum30}{n} \times 100 \quad (5)$$

$$R^2 =$$

$$\left(\frac{\sum_{i=1}^n (Cc \text{ or } Cr_{(p)} - Cc \text{ or } Cr_{(p) \text{ average}})(Cc \text{ or } Cr_{(m)} - Cc \text{ or } Cr_{(m) \text{ average}})}{\sqrt{\sum_{i=1}^n (Cc \text{ or } Cr_{(p)} - Cc \text{ or } Cr_{(p) \text{ average}})^2 \sum_{i=1}^n (Cc \text{ or } Cr_{(m)} - Cc \text{ or } Cr_{(m) \text{ average}})^2}} \right)^2 \quad (6)$$

Where, $Cc_{(p)}$ is the predicted compression index, $Cr_{(p)}$ is the predicted recompression index, $Cc_{(m)}$ is the measured compression index, $Cr_{(m)}$ is the measured recompression index, Sum20 is the number of predictions with error less than or equal to $\pm 20\%$, Sum30 is the number of predictions with error less than or equal to $\pm 30\%$, and n is the number of the cases for each database.

The steps of the methodology are also summarized in a simple flow chart presented in Fig. 1.

4. Development of the database

4.1 Experimental work

In this work, the geotechnical properties of the alluvial soils from southern Iraq have been experimentally determined. One hundred twenty undisturbed samples have been obtained from field exploration work for eight sites. The collection of the samples has been conducted as per the ASTM D1452/D1452M (2016). These samples have been collected from thirty-nine boreholes drilled to different

Table 1 Geotechnical properties of alluvial soils from Southern of Iraq

Site No.	LL, (%)	PI, (%)	wo, (%)	e_o	n_o	Cc	Cr
Site 1	21-59	5-31	10-49	0.412-1.389	0.292-0.582	0.060-0.426	0.005-0.056
Site 2	34-51	11-23	26-41	0.686-1.187	0.407-0.543	0.170-0.360	0.012-0.057
Site 3	35-39	14-15	27-45	0.797-1.055	0.443-0.513	0.230-0.490	0.025-0.033
Site 4	41-44	19-20	29-40	0.729-1.106	0.422-0.525	0.210-0.440	0.028-0.037
Site 5	37-49	15-24	32-39	0.885-1.095	0.469-0.523	0.230-0.270	0.020-0.031
Site 6	41-49	19-26	28-40	0.685-1.063	0.407-0.515	0.180-0.410	0.022-0.035
Site 7	31-45	10-21	34-42	1.067-1.086	0.516-0.521	0.260-0.300	0.033-0.038
Site 8	31-39	10-15	34-39	1.067-1.131	0.516-0.531	0.260-0.280	0.033-0.035

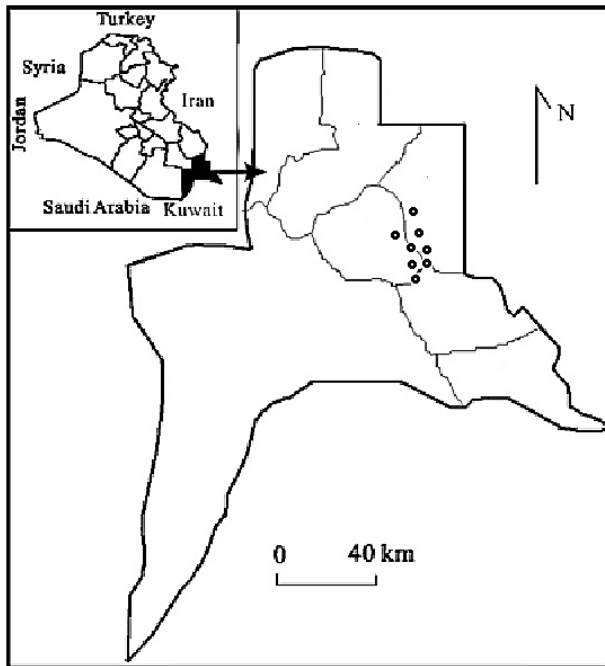


Fig. 2 The location of sites

depths, where the depth of the boreholes ranged from 1 to 30 meters.

The drilled boreholes represent the major stratigraphic units that formed the investigated area as part of the lower Mesopotamian region (Fig. 2). The sediments in this region consist of Quaternary sediments of two main deposits: surficial fine-grained deposits and coarse-grained sediments. The top layers of the fine-grained sediments compose of clays. The clay of these sediments was classified as normally to slightly overconsolidated alluvial type (Hanzawa 1977, Saeedy and Millah 1990, Al-Taie 2015).

In order to build the main database, the collected undisturbed alluvial soil samples have been subjected to experimental testing program. The basic properties (including liquid limit, plastic limit, plasticity index and natural water content) have been determined in according to the ASTM specifications (ASTM D 2216, ASTM D 4318). Consolidation properties have been determined, one hundred twenty standard one-dimensional consolidation tests have been conducted. The consolidation test has been conducted according to the specifications of ASTM D2435-04 (2011). From the analysis of the consolidation results, different consolidation parameters including initial void

ratio (e_o), initial porosity (n_o), compression index (Cc), and recompression index (Cr) have been determined. Table 1 summarizes the main geotechnical properties, and Figs. 3-5 present the relationship of the void ratio and the effective applied stresses for the undisturbed samples as obtained from the one-dimensional consolidation conditions.

4.2 Data collection from the literature

As part of the database development for this work, extensive literature review has been conducted to improve the database of the compression and recompression indices. As a result many papers have been reviewed (e.g., Kaufman and Sherman 1964, MacDonald and Sauer 1970, Koumoto and Kaku 1987, Ferreira Gomes and Ladeira 1995, Chin and Liu 1996, Tan *et al.* 2004, INEEL 2005, Campolunghi *et al.* 2007, Harsini *et al.* 2007, Pant 2007, Bozzano *et al.* 2008, Isik 2009, Lee *et al.* 2011, Samir 2013, Lat *et al.* 2018). As it was aimed to collected as many data points as possible, there were difficulties encountered in the collection of the data due to lack of the presentation of all the properties of the soils (i.e., unit weight, Atterberg limits, initial water content, and specific gravity) being tested in the consolidation equipment. However, the authors noticed that all the reviewed studies provided the value of initial void ratio. Hence, it was decided to move forward with the analyses and the model development using only the void ratio as the accuracy of the developed correlations was very good for the compression index and reasonable for the recompression index considering only the initial void ratio as will be demonstrated in the results section. Also, it is always required in practice to develop simple correlations which was also one of the factors which contributed to the authors decision. The data collected from literature review are summarized in Table 2. Based on the results of the experimental program of the paper and the reviewed papers, it was possible to collected 227 data points for the compression index and 216 data points for the recompression index. In addition, the basic statistical indicators for the collected data are presented in Tables 3 and 4 for the compression index (Cc) and recompression index (Cr) databases, respectively.

5. New model of the compression index and comparison with available correlations

This section discusses the development of a new model

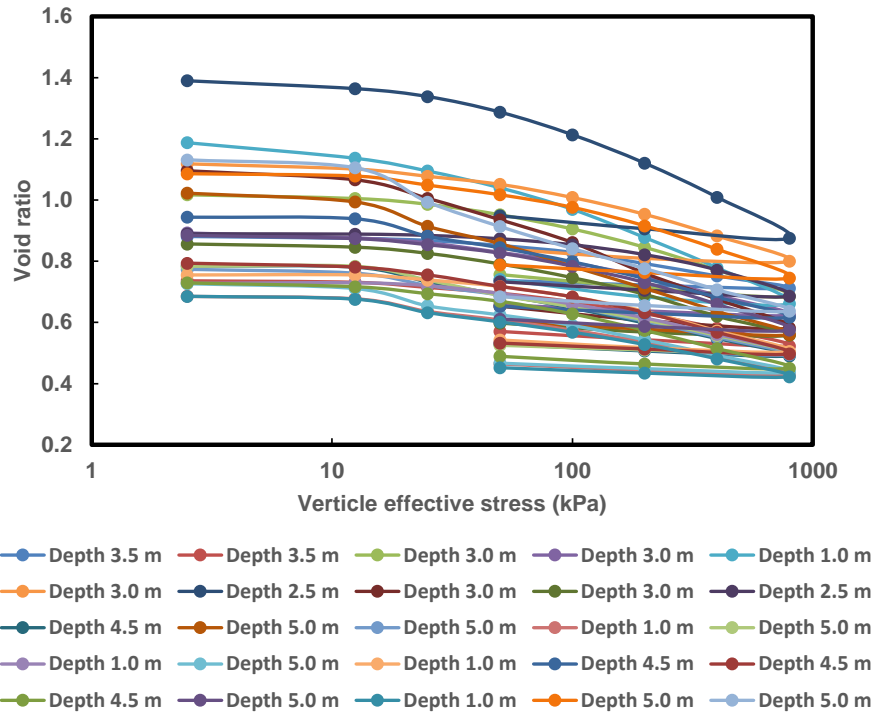


Fig. 3 Void ratio versus vertical effective stress of the undisturbed samples for depth range of 1.0 to 5.0 m

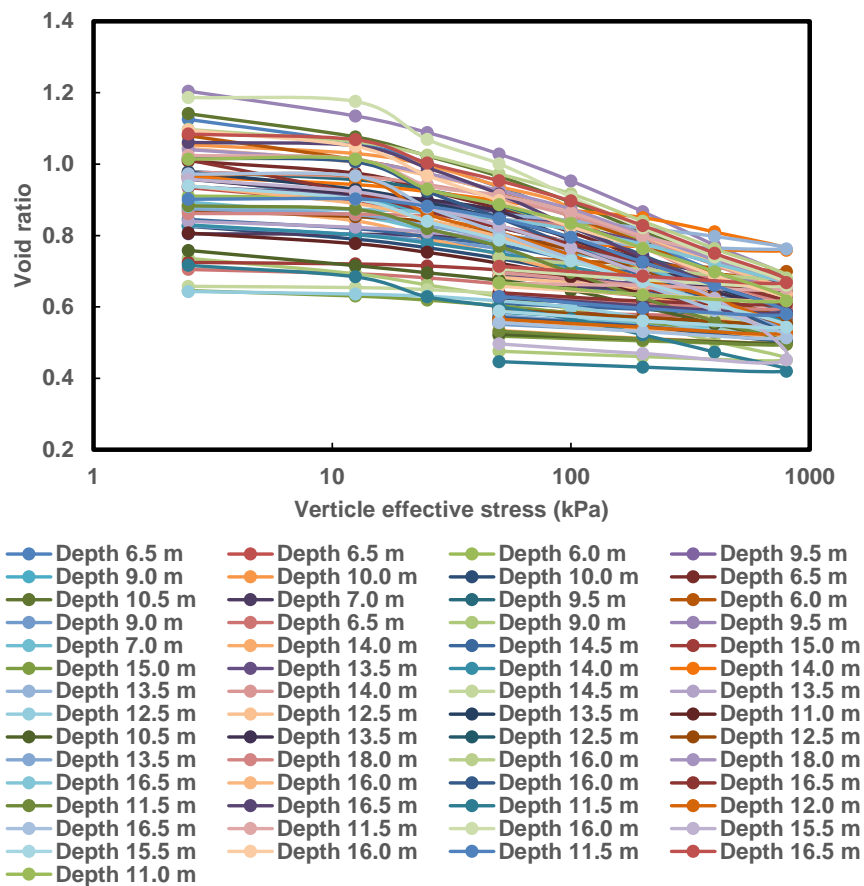


Fig. 4 Void ratio versus vertical effective stress of the undisturbed samples for depth range of 6.5 to 18.0 m

to predict the compression index and compare its performance with available empirical correlations. It should be stated that the empirical correlations employed in the

comparisons for the case of the compression index are the correlations of Hough (1957), Cozzolino (1961), Sowers (1970), and Bowles (1979) as these are the only available

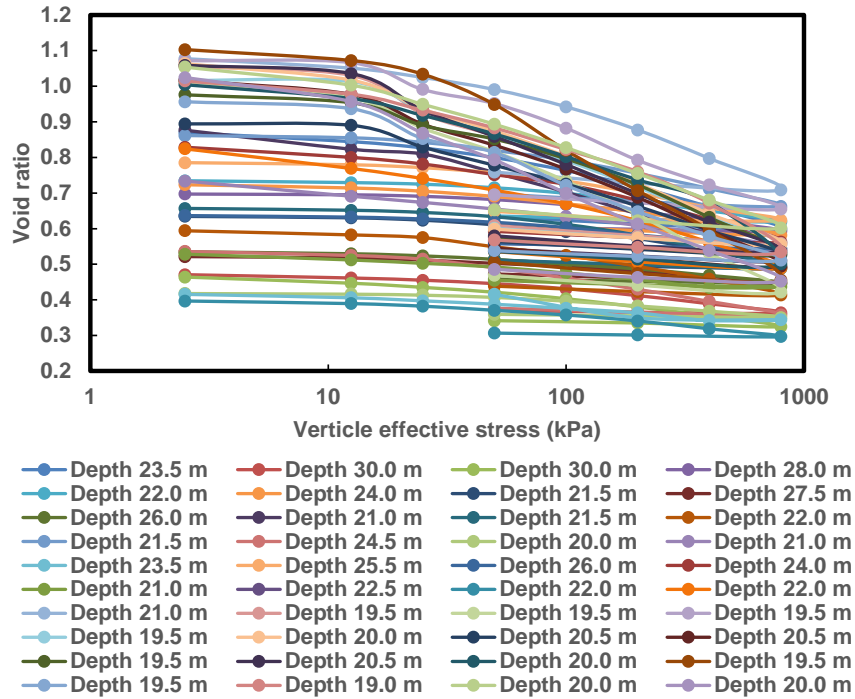


Fig. 5 Void ratio versus vertical effective stress of the undisturbed samples for depth range of 19.0 to 30.0 m

Table 2 Summary of database collected from literature

Soil description and location	LL (%)	PI (%)	e_o	C_c	C_r	Reference
Alluvium Clay, Setif, Algeria	59	30	0.669	0.09	0.02	Samir (2013)
Holocene deposits, Khuzestan, Iran	34-61	13-33	0.516-1.994	0.15-0.37	0.02-0.09	Harsini <i>et al.</i> (2007)
Taipei Clay, Taiwan	-	-	1.08-1.17	0.36-0.40	0.042	Chin and Liu (1996)
Old alluvium	-	-	0.639	0.18	0.03	INEEL (2005)
Ulleung Basin sediments, Changho - South Korea	67-115	33-50	3.09-3.67	1.16-1.19	0.061-0.075	Lee <i>et al.</i> (2011)
Holocenic alluvial deposits, Roma, Italy	-	-	0.6-2.4	0.23-1.20	0.008-0.066	Campolunghi <i>et al.</i> (2007)
Ariake Clay, Tokyo, Japan	-	-	1.17-2.03	0.287-1.115	-	Koumoto and Kaku (1987)
Aveiro city, west coast, Portugal	-	-	0.441-1.666	0.058-0.708	-	Ferreira Gomes and Ladeira (1995)
Soil description and location	LL (%)	PI (%)	e_o	C_c	C_r	Reference
Cohesive sediments, Turkey	-	-	0.495-1.773	-	0.015-0.128	Isik (2009)
Mississippi River Valley, Louisiana	31-81	6-56	0.923-1.325	0.16-0.84	0.007-0.056	Kaufman and Sherman (1964)
Till Soil, Saskatchewan, Canada	24-27	12-13	0.315-0.370	0.08-0.11	0.01-0.022	MacDonald and Sauer (1970)
alluvial clay ukit Tinggi, Klang, Malaysia	-	-	0.90-3.69	0.38-2.255	0.061-0.282	Tan <i>et al.</i> (2004)

Table 3 Statistics of the collected data of the compression index

Indicator	e_o	C_c
Minimum value	0.310	0.057
Maximum value	3.700	2.255
Range	3.390	2.198
Average of values	1.115	0.364
Standard deviation of the values	0.598	0.364

Table 4 Statistics of the collected data of the recompression index

Indicator	e_o	C_r
Minimum value	0.3100	0.0050
Maximum value	3.7000	0.2820
Range	3.3900	0.2770
Average of values	1.0383	0.0494
Standard deviation of the values	0.5863	0.0541

correlation in the literature which correlate the compression index with the initial void ratio. Table 5 presents the

mathematical expression of these correlations.

As stated in the methodology, the regression analysis has

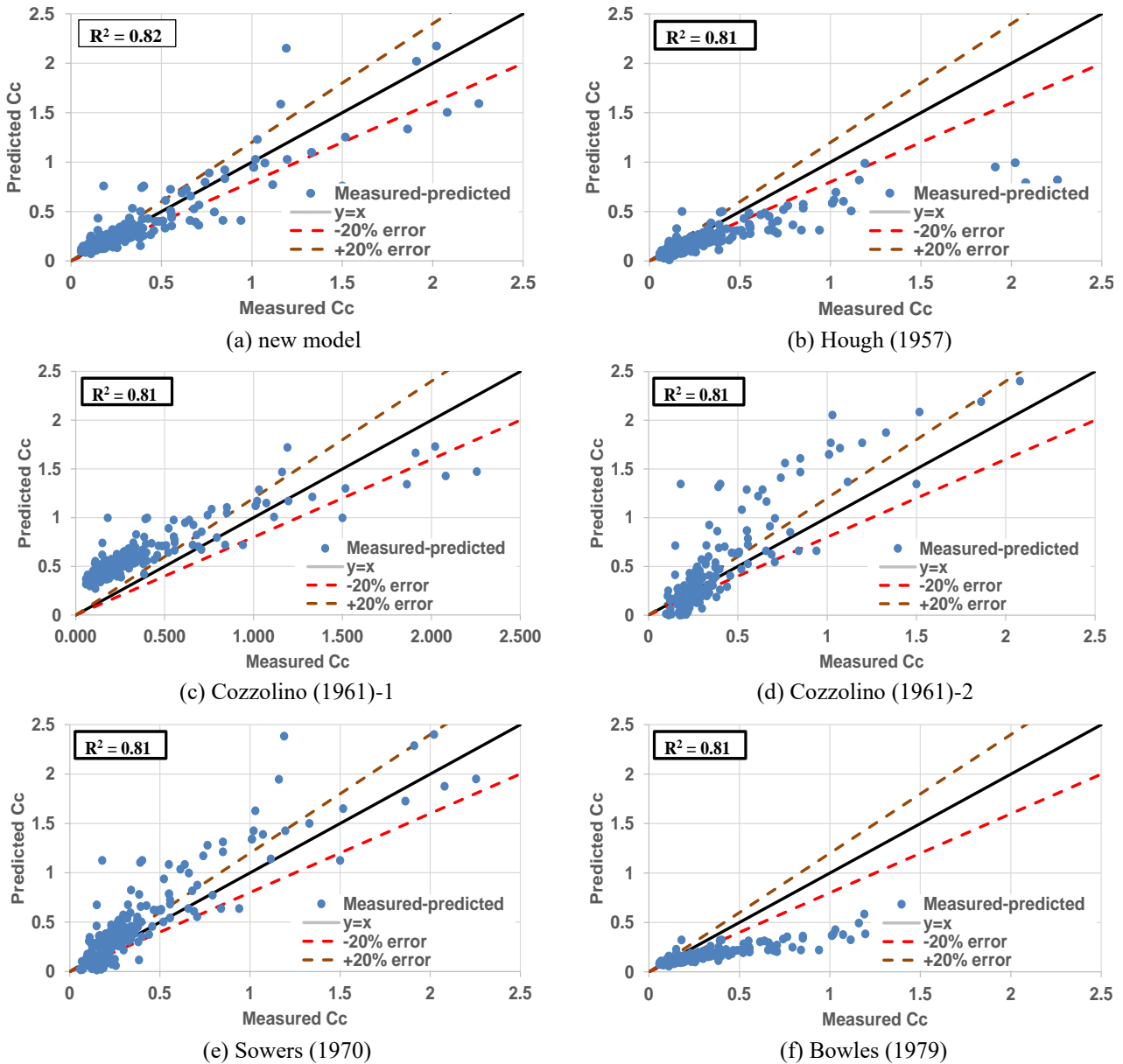


Fig. 6 Relationship between measured and predicted compression index for (a) new model, (b) Hough (1957), (c) Cozzolino (1961)-1, (d) Cozzolino (1961)-2, (e) Sowers (1970), and (f) Bowles (1979)

Table 5 Available correlations to predict the compression index

Correlation	Reference	Identifier in this paper
$Cc = 0.29(e_o - 0.27)$	Hough (1957)	Hough (1957)
$Cc = 0.246 + 0.43(e_o - 0.25)$	Cozzolino (1961)	Cozzolino (1961)-1
$Cc = 1.21 + 1.055(e_o + 1.87)$	Cozzolino (1961)	Cozzolino (1961)-2
$Cc = 0.75(e_o - 0.5)$	Sowers (1970)	Sowers (1970)
$Cc = 0.156e_o + 0.0107$	Bowles (1979)	Bowles (1979)

been used to develop the new model to predict the compression index. The NCSS software has been used in conducting the regression analysis. Several trials have been made in the regression analysis by testing the accuracy of the proposed model using different available standard regression models. After several trials a model has been chosen based on its accuracy in comparison with the measured data and also in comparison with the available

empirical correlations. The new model is shown in Eq. (7).

$$Cc = (0.16129 + 0.35501e_o)^2 \tag{7}$$

Fig. 6(a)-(c) compare the relationship between the measured and predicted compression index with the perfect fit line ($y=x$) and error range of $\pm 20\%$ for the new model, Hough (1957) correlation, Cozzolino (1961) correlation, Sowers (1970) correlation, and Bowles (1979) correlation,

Table 6 Accuracy performance indicators of the new compression index model and the available correlations

Correlation	MAE	RMSE	Mean	P20 (%)	P30 (%)
New model	0.09	0.16	1.09	57	71
Hough (1957)	0.13	0.25	0.79	32	55
Cozzolino (1961)-1	0.29	0.31	2.37	7	11
Cozzolino (1961)-2	0.23	0.35	0.64	19	32
Sowers (1970)	0.15	0.22	1.24	26	39
Bowles (1979)	0.19	0.33	0.67	12	31

respectively. The figures also show the obtained coefficient of determination (R^2) for each correlation. It is clear from the figures that the new model provides the lowest scatter of the predictions around the perfect fit line and also

provide lower points with error outside the $\pm 20\%$, although the results of the coefficient of determination show minor improvement in the accuracy using the new model compared with the available correlations.

Table 6 presents the results of the MAE, RMSE, Mean, P20, and P30 for the new model and the available correlations, respectively. It is evident from the figures that the new model predicts the compression index with error lower than the available correlations, where it scored values of MAE and RMSE much less than the available empirical correlations (MAE=0.085 and RMSE=0.155). In addition, the new model also scored better in terms of the mean, and percentage of predictions with error range of $\pm 20\%$ (P20) and $\pm 30\%$ (P30), where the mean, P20, and P30 values are equal to 1.09, 57%, and 71%, respectively. Hence, it can be concluded that the new model provides much better

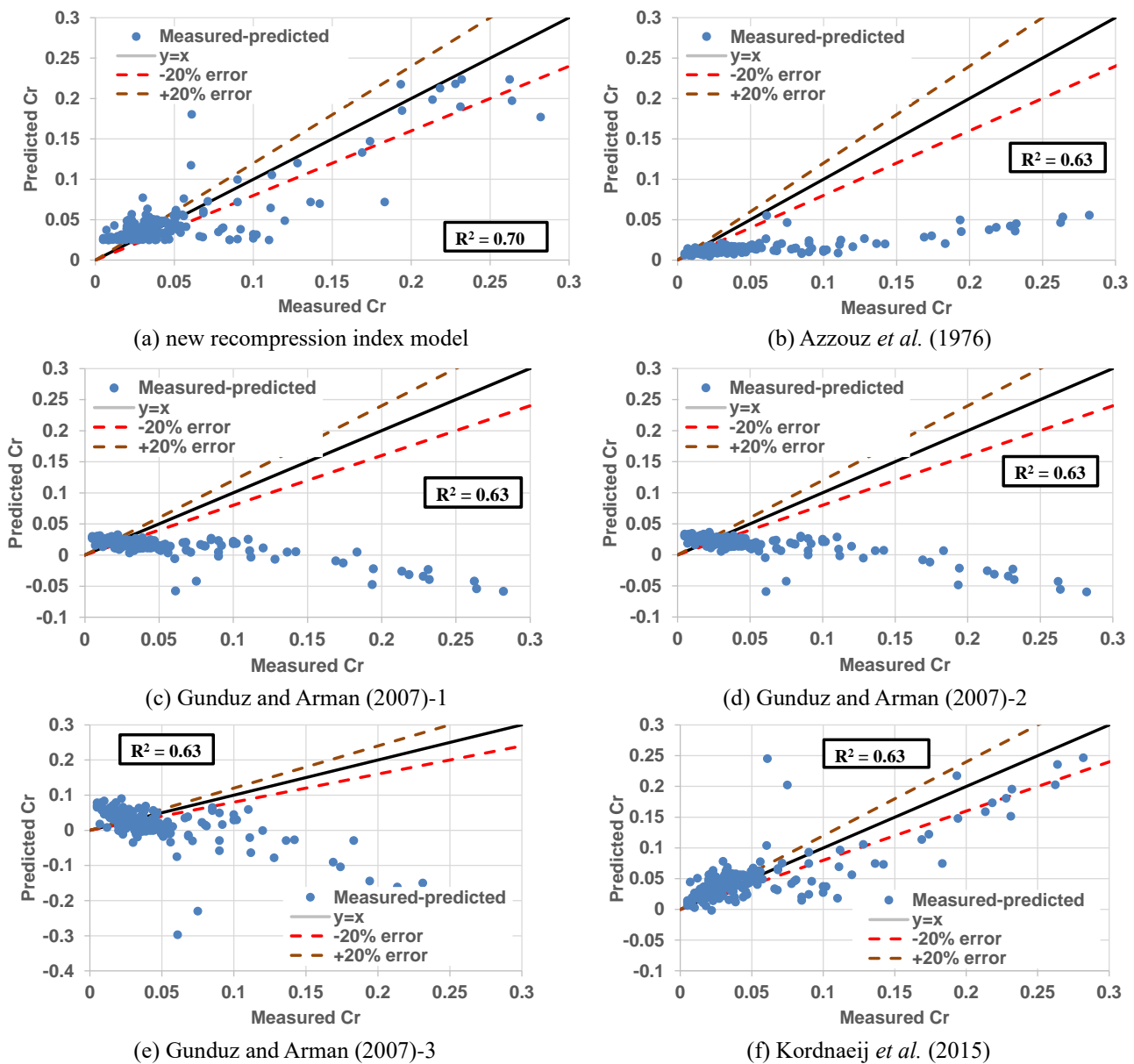


Fig. 7 Accuracy performance of the new recompression index model in comparison with the available correlations for (a) new model, (b) Azzouz *et al.* (1976), (c) Gunduz and Arman (2007)-1, (d) Gunduz and Arman (2007)-2, (e) Gunduz and Arman (2007)-3, and (f) Kordnaeij *et al.* (2015)

Table 7 Available correlations to predict the recompression index

Correlation	Reference	Identifier in this paper
$Cr = 0.015 (e_o + 0.007)$	Azzouz <i>et al.</i> (1976)	Azzouz <i>et al.</i> (1976)
$Cr = 0.041 - 0.0268 e_o$	Gunduz and Arman (2007)	Gunduz and Arman (2007)-1
$Cr = 0.045 - 0.0283 e_o$	Gunduz and Arman (2007)	Gunduz and Arman (2007)-2
$Cr = 0.126 - 0.115 e_o$	Gunduz and Arman (2007)	Gunduz and Arman (2007)-3
$Cr = -0.024 + 0.0732e_o$	Kordnaeij <i>et al.</i> (2015)	Kordnaeij <i>et al.</i> (2015)

accuracy based on the obtained values of MAE, RMSE, Mean, P20, and P30, although the scored coefficient of determination for the new model is close to the corresponding values obtained from the available correlations. Thus, the new correlation can be recommended to be used in predictions of the compression index for alluvial soils.

In addition, it can be concluded based on the presented results in Fig. 6 and Table 6 that the correlation of Hough (1957) can be ranked second in terms of the accuracy of the prediction as this correlation scored MAE lower than the other existed empirical correlations (MAE=0.133) and P20 and P30 values higher than the other available empirical correlations (P20=32% and P30=55%). On the other hand, Cozzolino (1961)-1 correlation provides the worst accuracy of prediction as it scored the lowest MAE. Cozzolino (1961)-1 correlation was only able to predict 7% of results with error range less than or equal to 20%, and 11% of results with error range less than or equal to 30%. This correlation also scored a mean value much higher than the optimum value (2.37 in comparison with optimum mean value of 1.00).

6. New model of the recompression index and comparison with available correlations

A new model is developed in this section to predict the recompression index of alluvial soils. Furthermore, the accuracy of the new recompression index model has been compared with the empirical correlations proposed by Azzouz *et al.* (1976), Gunduz and Arman (2007), and Kordnaeij *et al.* (2015) as these also the only empirical correlations available in the literature which utilized the initial void ratio as the only independent variable to predict the recompression index. These correlations are shown in Table 7.

It is worthy to state that the approach employed in the development of the new compression index model has been used to develop the new model of the recompression index of the alluvial soils. The most accurate model found from the regression analysis is show in Eq. (8).

$$Cr = -0.0257e_o^3 + 0.1395e_o^2 - 0.1326e_o + 0.06 \quad (8)$$

Fig. 7(a)-(f) compare the relationship of the predicted-measured recompression index with the perfect fit line and

Table 8 Accuracy performance indicators of the new recompression index model and available correlations

Correlation	MAE	RMSE	Mean	P20 (%)	P30 (%)
New model	0.02	0.03	1.32	37	50
Azzouz <i>et al.</i> (1976)	0.03	0.06	0.46	5	12
Gunduz and Arman (2007)-1	0.04	0.07	0.69	11	18
Gunduz and Arman (2007)-2	0.04	0.07	0.79	15	25
Gunduz and Arman (2007)-3	0.06	0.12	1.14	12	18
Kordnaeij <i>et al.</i> (2015)	0.02	0.03	1.33	26	40

lines of error range of $\pm 20\%$. It is evident from the figures that the new recompression index model provides better predictions compared with the available correlations. In addition, it is also obvious from Fig. 7(c)-(f) that the correlations of Gunduz and Arman (2007), Kordnaeij *et al.* (2015) provide negative values for some of the cases. Thus, although the coefficient of determination is very close for the new model ($R^2=0.70$) in comparison with the available correlations ($R^2=0.62$), the figures clearly show that the new model provide better accuracy.

Table 8 presents the results of the MAE, RMSE, Mean, P20, and P30, respectively for the developed model and the available correlations to provide more focused insight into the prediction accuracy. Based on the results of Table 8, it is obvious that the new model offers better accuracy as it scored better values for the MAE (0.017), RMSE (0.028), P20 (37%), and P30 (50%). Thus, the new model provides better alternative to predict the recompression index for alluvial soils. Furthermore, it is obvious from Fig. 7(a)-(e) that Gunduz and Arman (2007)-3 correlation scored the largest average error with MAE=0.06 and RMSE=0.12, while Azzouz *et al.* (1979) correlation scored the lowest P20 and P30 with values equal to 5% and 12%, respectively. On the other hand, the correlation of Kordnaeij *et al.* (2015) scored second in terms of the P20 and P30 with values of 26% and 40%, respectively.

7. Conclusions

This study concerned with the development of new models that could be used with confidence to predict the compression and recompression indices (compressibility parameters) of alluvial soils to reduce the budget and time needed to conduct consolidation test and thus, to reduce cost and time required to calculate the consolidation settlement of alluvial soils. Therefore, databases have been developed by conducting experimental tests and collecting results from the literature. The experimental work involved obtaining 120 undisturbed samples from eight sites and testing these samples in the laboratory. The data collection involved an extensive literature survey of all of the past studies associated with the compressibility parameters of alluvial soils.

The new models have been established using the developed database utilizing nonlinear regression analysis. In addition, the predictions of the new models have been

compared with the predictions of the correlations available in previous studies. The accuracy indicators used in the comparisons were the mean absolute error, root mean square error, mean, percentage of predictions within error range of $\pm 20\%$, percentage of predictions within error range of $\pm 30\%$, and coefficient of determination. The results of the comparisons showed that the new models provide predictions with accuracy much better than the available correlations. Thus, geotechnical engineers could use the new models with more confidence to predict the compression and recompression indices. These models will also save time and budget as they only use the initial void ratio to aid prediction of compressibility parameters with good accuracy.

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