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STATISTICAL EVALUATION OF GEOTECHNICAL CORRELATIONS

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ABSTRACT: Geotechnical correlations are widely used because it can provide fast and cost-effective means of parameter estimation using simple tests. Most of the current correlations were derived from data fitting of measurements for specific site conditions and need to be evaluated before used in other sites. During the correlation development, the deviation of the correlation from the measured values was evaluated using simple statistical measures. A better method of correlation evaluation may reduce the overall deviation of the geotechnical parameter. Amended Theil Inequality Coefficient (ATIC) is proposed as an evaluation tool because it has the advantage that it considers both position and trend conformities between observed and correlated values. To address the efficiency and rationality of ATIC, evaluation of, 92 compression index correlations by ATIC and different statistical measures was carried out. Comparison between the results showed that ATIC is efficient in assessing the best and worst correlations and it can be considered a good tool for correlations evaluation.

Keywords: Compression index correlations, Statistical evaluation, Correlation ranking, Geo-database

1. INTRODUCTION

The estimation of soil parameters using empirical correlations is widely used in geotechnical engineering [1]. Most important reasons are; direct measurements contains uncertainty, not always applicable, costly, and time-consuming [2], [3]. Thus, empirical correlations can provide fast and cost-effective means of parameter estimation using simple tests [4]. Most of these correlations were derived from data fitting of measurements at specific site conditions that may cause large deviation if used for other sites [5]–[7].

During the correlation development, the deviation of the correlation from the measured values was evaluated using simple statistical measures such as correlation coefficient (R) and determination coefficient (R^2) [5]–[11]. Better statistical evaluation may reduce the overall deviation of the estimated geotechnical parameter. Evaluation of different geotechnical correlations using statistical measures grabs the attention of many researchers for decades.

For shear strength parameters correlations; Hatanaka and Ushida [12] evaluated internal friction angle correlations with standard penetration test (SPT) results and proposed a rectified correlation that consider the effect of in-situ confining pressure. Nassaji and Kalantari [13] evaluated different undrained shear strength correlations with SPT N-Value. The authors used the standard deviation and visual inspection to evaluate different correlations.

Compression index (Cc) correlations were evaluated by many researchers. Nagaraj and Murthy [14] used experimental results to evaluate the applicability of 14 correlations using analytical examination. Giasi et al. [8] evaluated 32 correlations using experimental results for 46 soil samples from Italy. The authors used both ranking distance (RD) and Ranking Index (RI) to evaluate these correlations. The authors highlighted the accuracy problems of using RD and RI in correlations evaluation.

Yoon et al. [15] evaluated the results of using 15 empirical correlations to predict Cc of Korean coast marine clay using experimental results for more than 1200 consolidation tests. The authors used R to evaluate the newly, site-specific correlations and correlated/observed ratio (K-factor) for literature correlations. Rani and Rao [16] evaluated 12 correlations using one way and two way ANOVA along with mean absolute difference (MAD) to rank these correlations. Onyejekwe et al. [1] assessed the applicability of using 18 correlations for the estimation of Cc for Missouri region. The authors used the root mean square of deviation (RMSD), K-factor, RD, and RI to evaluate the correlations. Lee et al. [17] used R^2 and MAD to evaluate 29 correlations based on experimental results in South Korea.

Most of the above used statistical measures shortcoming that it considers position conformity or trend conformity separately. This shortcoming may cause misjudgment and wrong selection of best correlation. This paper introduced Amended Theil Inequality Coefficient (ATIC) method as a tool for correlation evaluation. ATIC method has the advantage that it considers both position and trend conformities in the overall ranking process. The viability of using ATIC method to evaluate geotechnical correlations is addressed and compared with other statistical evaluation measures.

The Cc correlations shall be considered in this paper as test-case. The reasons are: Cc determination is complex and time consuming that made empirical correlations more important; many correlations for different soil conditions; previous attempts of correlation evaluation were done; and its development starts as early as 1944 and new correlations still being developed [17].

2. USED DATA

Subsurface investigation reports were collected from Egypt, UAE, Iraq, and Indonesia. The collected reports contained field and laboratory tests results for more than 35,000 boreholes collected during the last three years. The most reliable boreholes were entered with consistent and unified units into customized geotechnical database. The data were checked with the source data to ensure the quality and consistency of information. To serve the research needs, only 27 tables were filled with 5087 boreholes

Data for this study was collected from the database with the condition that the sample has the all needed independent parameters to maintain same level of consistency and accuracy. Data was validated and only true outliers were excluded considering the very different characteristics of soils in the above countries. A total of 82 records were found to be eligible for the research needs. Table 1 shows descriptive statistic for the used soil properties.

Table 1 Used soil properties descriptive statistics

Property	Range	Mean	Std. Dev.
Initial Voids Ratio	0.32 - 4.35	1.58	0.84
Bulk Density (t/m^3)	1.04 - 2.29	1.61	0.31
Water Content (%)	11.9 - 168.1	57.15	31.09
Liquid Limit (%)	17.1 - 166.2	62.68	25.22
Plasticity Index (%)	2.48 - 113.9	30.71	17.84
Compression Index	0.07 - 1.66	0.57	0.3

Std. Dev. is the standard deviation

3. STUDIED CORRELATIONS

Several correlations were developed to relate Cc with field state properties and intrinsic soil properties. A total of 92 correlations were considered in this study as shown in Table 2.

Table 2 Studied Cc correlations

Cor. ID	Formula [Ref.]	Cor. ID	Formula [Ref.]
C01	$C_c = 0.29(e - 0.27)$ [18]	C47	$C_c = 0.01(L_L - 10.9)$ [15]
C02	$C_c = 0.156e + 0.0107$ [1]	C48	$C_c = 0.0037(L_L + 25.5)$ [6]
C03	$C_c = 1.21 + 1.005(e - 1.87)$ [19]	C49	$C_c = 0.0063(L_L - 10)$ [5]
C04	$C_c = 0.35\,(e - 0.5)$ [18]	C50	$C_c = 0.0075L_L$ [11]
C05	$C_c = 0.43(e - 0.25)$ [19]	C51	$C_c = 0.012L_L$ [11]
C06	$C_c = 0.54(e - 0.23)$ [20]	C52	$C_c = 0.018\,(L_L - 20.7)$ [7]
C07	$C_c = 0.4(e - 0.25)$ [21]	C53	$C_c = 0.014I_P + 0.02$ [15]
C08	$C_c = 0.256 + 0.43(e - 0.84)$ [19]	C54	$C_c = 0.0104I_P + 0.046$ [22]
C09	$C_c = 0.434(e - 0.336)$ [23]	C55	$C_c = 0.014I_P + 0.165$ [15]
C10	$C_c = 0.208e + 0.0083$ [24]	C56	$C_c = 0.0042I_P + 0.165$ [6]
C11	$C_c = 0.75(e - 0.5)$ [21]	C57	$C_c = 0.0115W_c$ [25]
C12	$C_c = 0.2e^{1.6}$ [26]	C58	$C_c = 0.01\,(W_c - 5)$ [21]
C13	$C_c = 1.15(e - 0.35)$ [27]	C59	$C_c = 0.01\,(W_c - 7.594)$ [28]
C14	$C_c = 1.15(e - 0.91)$ [27]	C60	$C_c = 0.0093\,W_c$ [7]
C15	$C_c = 1.15e$ [27]	C61	$C_c = 0.015\,(W_c - 8)$ [20]
C16	$C_c = 0.54(e - 0.37)$ [15]	C62	$C_c = 0.001766\,W_c^2 + 0.00593\,W_c - 0.135$ [24]
C17	$C_c = 0.39(e - 0.13)$ [15]	C63	$C_c = 0.013\,(W_c - 3.85)$ [15]
C18	$C_c = 0.37(e - 0.28)$ [15]	C64	$C_c = 0.01\,(W_c + 2.83)$ [15]
C19	$C_c = 0.46(e - 0.28)$ [6]	C65	$C_c = 0.01\,(W_c - 11.22)$ [15]
C20	$C_c = 0.39e$ [14]	C66	$C_c = 0.0135W_c - 0.1169$ [6]
C21	$C_c = 0.42(e - 0.5)$ [5]	C67	$C_c = 0.01\,W_c$ [21]
C22	$C_c = 0.2608e$ [11]	C68	$C_c = 0.85\left(\frac{W_c}{100}\right)^{1.5}$ [29]
C23	$C_c = 0.3921e$ [11]	C69	$C_c = 0.0066W_c$ [5]
C24	$C_c = 0.2237e_L$ [8]	C70	$C_c = 0.014\,(W_c - 22.7)$ [7]
C25	$C_c = 0.2343e_L$ [8]	C71	$C_c = 0.005\,G_S\,I_P$ [1]
C26	$C_c = 0.274e_L$ [8]	C72	$C_c = 0.4(e + 0.001W_C - 0.25)$ [21]
C27	$C_c = \frac{0.0018n}{1-0.0109n}$ [9]	C73	$C_c = 0.489\left[\ln(G_S)\left(\frac{1+e}{G_S}\right)^2 + 0.296\right]$ [23]
C28	$C_c = \frac{0.00269n}{1-0.0115n}$ [9]	C74	$C_c = 0.1525G_S\left(\frac{1+e}{G_S}\right)^2$ [23]
C29	$C_c = 1.0584n^2 + 0.0885n$ [11]	C75	$C_c = 0.46e - 0.049G_S + 0.0023$ [6]
C30	$C_c = 0.5\left(\frac{\gamma_w}{\gamma_d}\right)^{2.4}$ [23]	C76	$C_c = 0.411e + 0.00058L_L - 0.156$ [28]
C31	$C_c = 2.4 - 1.66\,\gamma_d$ [15]	C77	$C_c = 0.37(e + 0.003L_L - 0.34)$ [21]
C32	$C_c = 1.15 - 0.66\,\gamma_d$ [15]	C78	$C_c = 0.37(e + 0.003L_L + 0.0004W_C - 0.34)$ [21]
C33	$C_c = 1.1014 - 0.579\gamma_d$ [6]	C79	$C_c = 0.4965e - 0.0014W_C - 0.123$ [6]
C34	$C_c = 0.0046(L_L - 9)$ [19]	C80	$C_c = 0.247e + 0.004L_L + 0.01W_C + 0.021$ [6]
C35	$C_c = 0.006(L_L - 9)$ [21]	C81	$C_c = 0.185\left(G_S\left(\frac{\gamma_w}{\gamma_d}\right)^2 - 0.144\right)$ [23]
C36	$C_c = \frac{(L_L-13)}{109}$ [28]	C82	$C_c = 0.141\,G_S\left(\frac{1+e}{G_S}\right)^{2.382}$ [23]
C37	$C_c = 0.0186(L_L - 30)$ [19]	C83	$C_c = 0.141\,G_S\left(\frac{\gamma_{sat}}{\gamma_d}\right)^{2.4}$ [23]
C38	$C_c = 0.009(L_L - 10)$ [1]	C84	$C_c = 0.173\,(1 + e)\,(\ln(L_L) - 3.01)$ [7]
C39	$C_c = 0.007(L_L - 7)$ [10]	C85	$C_c = 0.002343\,L_L\,G_S$ [14]
C40	$C_c = 0.017(L_L - 20)$ [7]	C86	$C_c = (1 + e)\,(0.095 + 0.00114W_C)$ [5]
C41	$C_c = 0.013(L_L - 13.5)$ [7]	C87	$C_c = 0.1905\,(1 + e)\,(\ln(W_C) - 3.03)$ [7]
C42	$C_c = 0.009(L_L - 8)$ [1]	C88	$C_c = 0.194e - 0.0025I_P + 0.0098W_C - 0.256$ [15]
C43	$C_c = 0.009L_L$ [1]	C89	$C_c = 0.538e + 0.002L_L - 0.0003W_C - 0.3$ [15]
C44	$C_c = 0.007(L_L - 10)$ [10]	C90	$C_c = 0.12e + 0.0065L_L + 0.0038W_C - 0.248$ [15]
C45	$C_c = 0.012(L_L + 16.4)$ [15]	C91	$C_c = 0.009W_C + 0.005L_L$ [7]
C46	$C_c = 0.011(L_L - 6.36)$ [15]	C92	$C_c = 0.009W_C + 0.002L_L - 0.1$ [21]

Where e: voids ratio, n: porosity, γ_d: dry density (g/cm^3), L_L: liquid limit, I_P: plasticity index, W_C: natural water content, and G_S: specific gravity

4. QUANTITATIVE ANALYSIS

The maximum, minimum, mean, and standard deviation of the correlated values were compared to those of the observed values as shown in Fig. 1. No general conclusion can be made based on the above measures except the scatter of the correlated values around the observed values.

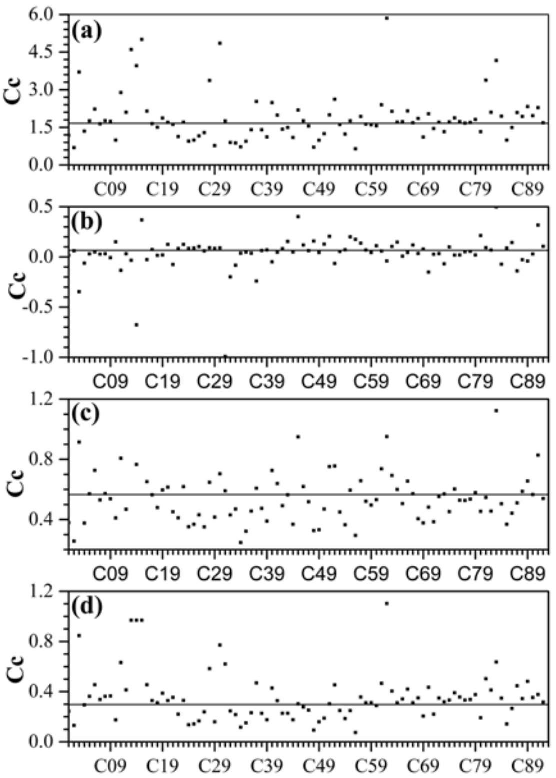

Fig. 1 Correlated values (a) Maximum, (b) Minimum, (c) Mean, and (d) Standard deviation with those of the observed values (solid line).

5. CORRELATIONS EVALUATION

Till now, there are no formal standards for evaluating the goodness-of-fit between the observed and correlated values, either visually or numerically [30]. In this section, ATIC method as a tool for correlation evaluation is introduced and compared with different statistical measures.

5.1. ATIC Method

Theil inequality coefficient (TIC) is widely used since 1977 because it is simple and easy to understand. However, it suffers of many flaws that have been discussed in detail by Song et al. [31] who proposed ATIC method. The ATIC covers many of the TIC method flaws; especially it considers both position and trend differences between the observed and correlated values using principle component analysis approach. The standard procedures and equations for correlations ranking based on ATIC method are given in Fig. 2.

Both position conformity coefficient, $D(X_o, X_c)$, and trend conformity coefficient, $T(X_o, X_c)$, ranges between 0 and 1. When the value is close to 1, it indicates better consistency between the observed and correlated values.

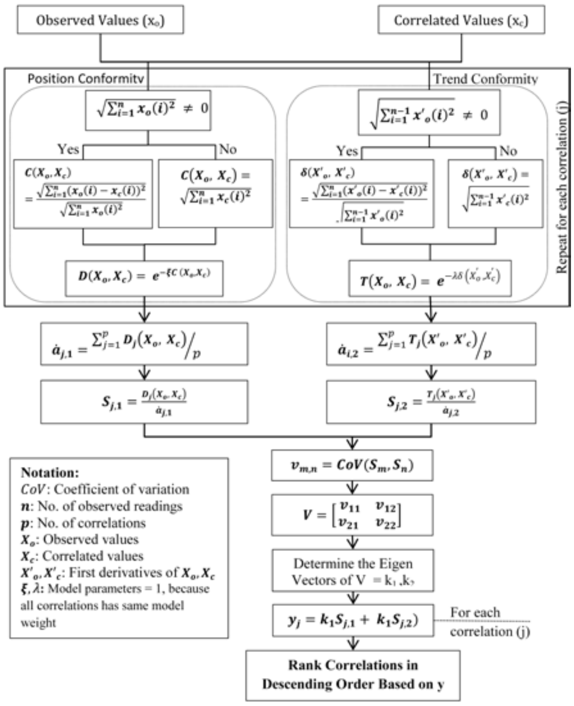

Fig. 2 Correlations ranking based on ATIC method.

ATIC method was used to rank the 92 Cc correlations. Summary of the results for the 5 top-most and bottom-most ranked correlations considering both position and trend is given in Table 3.

Table 3 ATIC results summary for the 10 top-most and 10 bottom-most ranked correlations

	Rank	Cor. ID	$\mathbf{D}(\mathbf{X_o}, \mathbf{X_c})$	$\mathbf{T}(\mathbf{X_o}, \mathbf{X_c})$	y_j
5 Top Cor.	1	C22	0.6474	0.4607	1.6259
	2	C80	0.6475	0.4566	1.6182
	3	C43	0.6405	0.4602	1.6175
	4	C10	0.6484	0.4557	1.6173
	5	C50	0.6346	0.4586	1.6077
5 Bot. Cor.	88	C03	0.2969	0.1419	0.6089
	89	C14	0.2710	0.1025	0.5025
	90	C13	0.1607	0.1025	0.3803
	91	C62	0.1980	0.0565	0.3310
	92	C15	0.0980	0.1025	0.3108

If position conformity was considered separately; C60 and C67 will be considered the best ranked, and C13 and C15 are the worst ranked correlations. When considering the trend conformity; C26 and C22 are the best ranked, and C62 and C15 are the worst ranked correlations.

5.2. Correlation and Determination Coefficient

Correlation (R) and determination coefficients (R^2) give an indication about the strength of linear association between the correlated and observed data [30]. Both R and R^2 were calculated between the observed and correlated values using Eq. (2) and Eq. (3) [32].

$$R = \frac{\sum_{i=1}^{n}(x_{oi}-\overline{x_o})(x_{ci}-\overline{x_c})}{\sqrt{\sum_{i=1}^{n}(x_{oi}-\overline{x_o})^2 \sum_{i=1}^{n}(x_{ci}-\overline{x_c})^2}} \quad (2)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(x_{oi}-\overline{x_o})(x_{ci}-\overline{x_c})}{\sqrt{\sum_{i=1}^{n}(x_{oi}-\overline{x_o})^2 \sum_{i=1}^{n}(x_{ci}-\overline{x_c})^2}}\right]^2 \quad (3)$$

Where x_{oi}, x_{ci} observed and correlated value for each point i, n: number of points, $\overline{x_o}$, $\overline{x_c}$: average of observed and correlated values, respectively.

The Cc correlations were ranked based on both coefficients and the best correlation is C29 that was ranked the 12th best based on ATIC method, the worst correlations are C53, C54, C55, and C56. Fig. 4.a and 4.b shows the values for the best and worst ranked correlations based on ATIC and $R\&R^2$ values, respectively with the observed values.

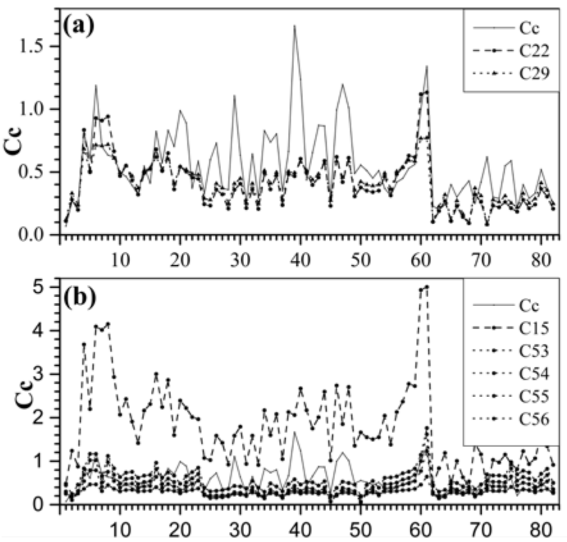

Fig. 3 Best (a) and worst (b) correlations based on ATIC method and $R\&R^2$ values.

Figure 4.a shows that both correlations are nearly accurate to predict the observed values nevertheless; C22 is more accurate especially at the extreme values. From Fig. 4.b it can be seen that the ATIC worst correlation (C15) is too far from the observed values in contrast to the worst correlations based on $R\&R^2$. The main reason for that the R and R^2 coefficients are sensitive for abrupt changes of the values and they only evaluate the trend of the values without considering their relative positions.

5.3. Mean Squared Deviation, Root Mean Squared Deviation, and Mean Absolute Difference

The Mean Squared Deviation (MSD), its square root (RMSD), and Mean Absolute Difference (MAD) are indicators of the difference between the positions of correlated values from the observed values. MSD, RMSD, and MAD were calculated between the observed and correlated values based on Eq. (4), Eq. (5), and Eq. (6), respectively [30].

$$MSD = \frac{\sum_{i=1}^{n}(x_{oi}-x_{ci})^2}{n} \quad (4)$$

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ci})^2}{n}} \quad (5)$$

$$MAD = \frac{\sum_{i=1}^{n}|x_{oi}-x_{ci}|}{n} \quad (6)$$

Where x_{oi} observed value for each point i, x_{ci}: correlated value for each point i, n: number of points

The Cc correlations were ranked based on those coefficients. The best correlation is C60 same results of ATIC method when considering only the position conformity. Fig. 5 shows the correlated values for the C22 and C60 in-line with the observed Cc values. It can be seen that both correlations are nearly accurate nevertheless C60 is not accurately follow the observed values trend. The worst correlation is C15 same as ATIC method rank.

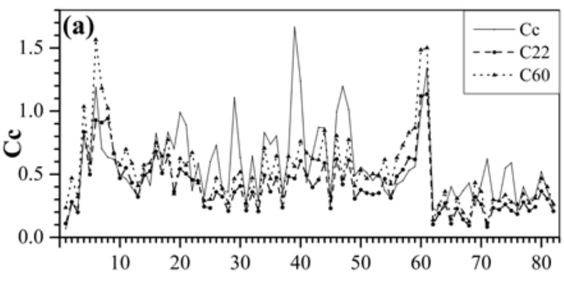

Fig. 4 Observed C_C values and correlated values for best correlations based on ATIC and MSD-RMSD-MAD values.

5.4. Ranking Index

The ranking index (RI) is proposed by Briaud and Tucker [33] to rank different methods of pile capacity determination as given in Eq. (9). The authors suggested that the lower the value of RI the better rank of the correlation.

$$RI = \mu \left|\ln\left(\frac{x_c}{x_o}\right)\right| + \sigma \left|\ln\left(\frac{x_c}{x_o}\right)\right| \qquad (9)$$

Where μ, σ : represents mean and standard deviation; and x_o, x_c : observed and correlated values

Some correlation resulted illogical negative values that can't be used in the normal log function in Eq. (9) that prevents successful ranking of all correlations. When ranking the other correlations, the best correlation was C67 that was ranked the 2nd best in ATIC method when considering only the position conformity. The worst correlation is C15, same as ATIC rank. Fig. 6 shows Correlations C67 and C22 in line with the observed C_C values.

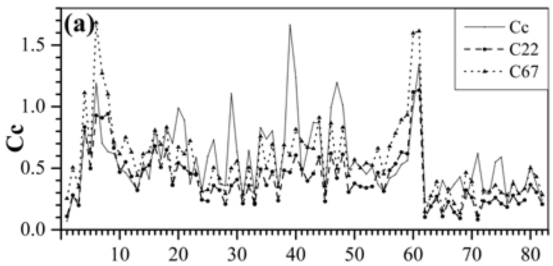

Fig. 5. Observed C_C values and correlated values for best correlations based on ATIC and RI.

5.5. Ranking Distance

The ranking distance (RD) was proposed by Cherubini and Orr [34] as a rational approach to compare between observed and correlated data as given in (10). The authors suggested that the lower the value of RD the better the accuracy and precision of the correlation.

$$RD = \sqrt{\left[1 - \mu\left(\frac{x_c}{x_o}\right)\right]^2 + \left[\sigma\left(\frac{x_c}{x_o}\right)\right]^2} \qquad (10)$$

All variables as defined in Eq. (9)

The best correlation based on RD values is correlation C02 that was ranked 58th best based on ATIC method. The worst correlation is C15, same as ATIC rank. During the data analysis, it was noted that the RD is biased for the odd ratios between correlated and observed values. Also, it considers only the position of the values without considering its trend. This may be the reasons for the large difference between the results of the ATIC method and RD. Correlations C02 and C22 are shown in Fig. 7 in-line with the observed C_C values.

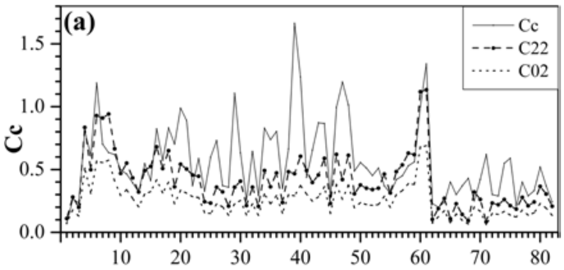

Fig. 6 Observed C_C values and correlated values for best correlations based on ATIC and RD.

6. CONCLUSION

This paper focused on the study of the validity and efficiency of Amended Theil Inequality Coefficient (ATIC) method for geotechnical correlations evaluation. ATIC has the advantage that it considers both position and trend conformities between the observed and correlated values. Total of 92 compression index correlations were used as test-case. Different statistical measures results that were used in the literature were compared with the results of the ATIC method.

The best correlation based on ATIC method was C22 and worst correlation was C15, both correlations relate compression index value with the initial voids ratio of the soil.

Based on R and R^2 coefficients, the best correlation is C29 and the worst correlations are C53, C54, C55, and C56. When visually inspect these correlations with the worst correlation based on ATIC, it was concluded that ATIC is more accurate. Both coefficients have shortcoming that they consider only the trend of the values without considering their relative position.

The best and worst correlations based on MSD, RMSD, and MAD is C60 and C15 respectively. When comparing these results with ATIC results, both methods give the same worst correlation, but different results for the best correlation. The MSD, RMSD, and MAD values have the shortcoming that they evaluate only the values' position around the average without considering its trend.

The RI best correlation was C67 that was ranked the 2nd best when considering only the position conformities in the ATIC method. The worst correlation was C15, same as ATIC rank. The RI considers only the position of the data that limits its ability for efficient correlation evaluation.

The RD best correlation was C02 that was ranked the 58th best based on ATIC method. The worst correlation was C15, same as ATIC rank. It was noted that RD is biased for the odd ratios between the correlated and observed values and it considers only values' position that may be considered the reason for the large difference between ATIC method results and RD results.

Based on the results of this paper, ATIC can be considered a good method of geotechnical correlations evaluation. Future research will concentrate on how to integrate ATIC method with expert knowledge to validate geotechnical correlations.

7. ACKNOWLEDGMENTS

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