

## Prediction of Compression Behaviour of Normally Consolidated Fine-Grained Soils

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**Abstract:** In this research, the effects of different physical and index properties of soil samples were investigated on compression index in order to find the most compatible properties and reliable equation based for a wide range of soil samples collected from different sites of Iran. For this purpose, one-dimensional consolidation tests were conducted utilizing conventional oedometer test on 26 soil samples at three different levels of void ratio. The compression index of each specimen was determined using data obtained from test results and correlation analysis was made using statistical software, SPSS. The results showed that the compression index,  $C_c$ , has a significant correlation with the most of index properties where its coefficient of correlation with structural properties was strongly greater than those related to inherent properties. Therefore the empirical equations which do not consider at least one structural parameter and use only intrinsic properties could not estimate the compression index properly. Furthermore a very simple and reliable equation was developed for estimation of the compression index and virgin curve of unconsolidated and normally consolidated fine-grained soils. Statistical analysis demonstrated that the proposed relationship predicts the compression index accurately in comparison with the existing relationships.

**Key words:** Consolidation • Compression index • Soil settlement • Compressibility of soils • Empirical equation

### INTRODUCTION

Compressibility characteristics of fine-grained soils are often the most important parameters for settlement evaluation of the founded layers. These characteristics are usually described using two well-known coefficients: the compression index,  $C_c$  and the coefficient of consolidation,  $C_v$ . The coefficient of consolidation,  $C_v$ , used to predict required time for a given amount of compression to take place and the compression index,  $C_c$ , is directly used for calculation of the settlement. The compression index is the slope of the straight-line portion of the pressure-void ratio curve on a semi logarithmic plot (virgin curve) which is usually obtained from one-dimensional consolidation test results. The virgin curve is generally a somewhat straight and flat curve on semi logarithm scale up to a certain pressure and followed by a somewhat smooth but rather pronounced transition into a steep and relatively straight line. But it is essentially straight line for unconsolidated and normally

consolidated fine-grained soils, where the slope and intercept of the line (virgin curve) depend on the index properties of the soils [1-4]. Since the conventional consolidation test requires undisturbed samples and is relatively time-consuming and expensive compared with standard index tests [5-6], many attempts have been made to predict compressibility behaviour of soils and correlate compression index,  $C_c$  with various index properties of soils. Burland [1] introduced the concept of *intrinsic* properties for soil samples which is reconstituted at a water content of 1-1.5 times the liquid limit to describe their strength and compressibility behaviour and showed the intrinsic compression curves of reconstituted clays are linear and at any given value of effective stress. Tsuchida [7] presented that the initial void ratio of slurry affects the compression curve. Bo *et al.*, [8] presented that for an ultra soft soil, from the virgin curve, three different compression indices can be determined for three stress ranges; 1-10, 10-100 and 100-1000 kPa. Furthermore, many empirical equations have been presented to predict

the compression index using various parameters by numerous researchers. Some have used single-variable empirical equations [9-16] and many others [17-24] proposed multi-variable equations for estimation of the compression index. Various parameters including; liquid limit, natural water content, in-situ void ratio, dry unit weight, plasticity index, void ratio at liquid limit, void ratio at plastic limit, specific gravity and shrinkage index were used for development of the equations.

Sridharan and Nagaraj [5] presented that the correlation between compressibility and liquid limit are limited, because a soil with lower shrinkage limit compresses more than a soil with a higher shrinkage limit, even though their liquid limit are the same. Sridharan and Prakash [25] showed that a family of compression curves is possible for a given soil sample depending upon its initial water content. Yoon *et al.*, [22] expressed that the application of the empirical equations suggested in previous studies result in large uncertainties in estimating the compression index of marine clayey soils in the coastal zone in Korea and proposed new empirical equations using natural water content, initial void ratio, liquid limit and plasticity index. Cerato and Lunegger [26] showed that intrinsic compression line may not be unique for a given soil and differs by the initial water content of reconstituted samples. Abbasi *et al.* [24] showed that a soil sample with different initial void ratio provided different values of compression index,  $C_c$  and concluded that the empirical relationships proposed only based on plasticity characteristics of soil can not estimate the value of  $C_c$  accurately. Ozer *et al.*, (2008) evaluated the performances of numerous empirical equations for estimation of the compression index and showed that the models of Azzouz *et al.*, [13] and Rendon-Herrero, [19] resulted in the best performance. It can be concluded from the literature that there is still uncertainty for using the previous empirical equations and mostly proposed for a certain and local condition. In this study, the effects of different physical and index properties were investigated on compression index in order to find the most compatible properties and reliable equation based for a wide range of soil samples collected from different sites of Iran.

## MATERIALS AND METHODS

**Collection of Soil Samples:** In this research, twenty six fine-grained soil samples were collected from different parts of Iran including Khozestan, Ardabil, Ghazwin, Esfahan and Tehran provinces. The soil samples were disturbed and picked up from test pits at 0.5- 1.0 meter

depth blew ground level. It was also tried to cover a wide range of index properties of the soil samples. Then, their physical and index properties including; grain size distribution, specific gravity ( $G_s$ ), Atterberg limit; liquid limit (LL), plastic limit (PL), shrinkage limit (SL), maximum dry density ( $\gamma_{dmax}$ ), optimum water content ( $\omega_{opt}$ ) and their classification (USCS) were determined based on ASTM standard test methods. Table 1 shows physical and index properties of the samples.

**Consolidation Test Apparatus:** Conventional oedometer tests were carried out for determination of compression index. For this purpose a standard and conventional oedometer apparatus having brass ring, 75 mm in diameter and 20 mm height was used. Two saturated porous stones and filter papers were assembled at top and bottom of the specimen and the cell containing ring and specimen was submerged and allowed to saturate for 24 hours. Then, vertical dead load was applied using loading device until there was no change in dial gauge reading for two consecutive hours. Other details of the test were performed in general accordance with the procedure described in American Society for Testing and Materials standard test method for one dimensional consolidation properties of soils [27].

**Preparation of the Specimens:** Substantial characteristics and initial different structural conditions of the soil samples are two main group factors affecting on the compression index of soils. For a given soil sample, substantial or inherent characteristics could be presented quantitatively by plasticity indices and specific gravity. Also, different properties including; water content, void ratio and dry density may be used for express the structural conditions of the samples. Therefore, in order to taking into account of these two main factors, conventional one-dimension consolidation tests were conducted on each soil sample at three different levels of void ratio. To do this, for each soil samples, three specimens were prepared with different initial water contents in which to be approximately 0.5, 0.8 and 1.2 times of their liquid limit (0.5LL, 0.8LL and 1.2LL). Then, the void ratios of the specimens were exactly calculated using phase relationships. Therefore, about seventy eight test specimens were prepared and tested. The specimens with initial water content about 1.2 times of liquid limit had slurry state and were filled in the fixed ring, taking care to prevent over topping. Filter papers were placed between specimen and saturated porous stones to prevent from movement of particles into the porous stone.

Table 1: Index properties of the soil samples

Soil No.	Texture			Compaction		Atterberg Limit			Classification (USCS*)
	Sand (%)	Silt (%)	Clay (%)	$\omega_{opt}$ (%)	$\gamma_{dmax}$ gr/cm <sup>3</sup>	LL (%)	PL (%)	SL (%)	
1	28	48	24	17.0	1.75	31.0	24.0	17.1	ML**
2	25	47	28	17.5	1.81	29.0	20.0	18.3	CL**
3	35	39	26	19.5	1.72	34.5	20.0	18.7	CL
4	30	38	32	19.6	1.74	36.0	23.5	22.5	CL
5	16	54	30	15.0	1.84	22.5	21.0	20.5	CL
6	28	48	24	18.5	1.75	32.5	22.0	20.8	CL
7	18	67	15	19.7	1.74	31.0	19.7	19.5	CL
8	49	35	16	25.5	1.55	70.0	28.0	17.9	CH**
9	33	61	6	21.2	1.66	46.0	25.0	23.8	CL
10	50	42	8	24.0	1.6	54.0	23.0	15.2	CL
11	46	43	11	25.5	1.48	64.0	31.0	16.8	CH
12	48	45	7	25.7	1.53	57.0	26.0	15.4	CH
13	38	50	12	21.4	1.67	38.0	26.0	24.3	CL
14	34	41	25	19.0	1.71	35.0	22.5	16.8	CL
15	49	49	2	22.0	1.64	56.0	27.0	21.1	CH
16	36	63	1	18.0	1.76	34.0	20.2	19.5	CL
17	26	62	12	20.0	1.68	37.0	25.0	21.9	CL
18	32	52	16	17.5	1.81	30.0	18.0	17.5	CL
19	44	56	0	22.3	1.64	40.0	23.0	22.2	CL
20	24	72	4	19.0	1.70	31.0	22.0	21.4	CL
21	23	66	11	22.2	1.62	41.5	26.5	24.3	ML
22	17	76	7	15.0	1.82	24.5	23.0	22.7	CL-ML
23	48	52	0	19.0	1.67	40.0	22.0	19.7	CL
24	26	67	7	17.0	1.73	31.0	20.0	20.0	CL
25	25	62	13	17.0	1.79	30.0	20.2	18.0	CL
26	28	57	15	20.0	1.67	34.0	23.0	20.8	CL

\* USCS: Unified Soil Classification System

\*\* CH: Clay with high plasticity CL: Clay with low plasticity ML: Silt with low Plasticity

After trimming top of the specimens and displacement of the upper porous stone and filter paper, the setting load (about 5.0 kPa) was applied and the set was left for 24 hours for fully saturation of the specimen. For other two groups of specimens which their initial water content were equal 0.5 and 0.8 times of their liquid limit, the specimens were enough strength to compact with a minimum energy in a separate large mold. Then, the specimen ring was pushed into the compacted sample, cut off about 3 cm of soil specimen from one end of the sample and carefully removed the material around the ring. The top and bottom of the ring was trimmed and placed on the odometer cell. Saturation of the specimen and applying setting load was made as mentioned before. Other procedures were made according to the standard test method.

## RESULTS AND DISCUSSION

### Compressibility Characteristics of the Samples:

As mentioned, one dimensional consolidation tests were conducted on each soil sample at three different initial void ratios. At the end of each test, the sample was removed from the ring and dried in oven to obtain its final dry weight, water content and void ratio as well as their

void ratio at each load increment. Then, the variation of void ratio versus pressure was plotted for each specimen on a semi logarithmic scale. Figures 1 presents the compression test results for the soil sample No. 8 and Figure 2 shows the compression line for sample No.18 at different levels of initial void ratio. Also, Figure 3 shows the variation range of compression index for specimens with different liquid limit and quite same initial void ratios and Figure 4 shows virgin curves for the samples with same initial void ratio ( $e_o = 0.7$ ) but different amounts of liquid limit.

As it is obvious from Figures 1, 2 and 4 and confirmed for the all of the specimens, it was found that the variation of void ratio ( $e$ ) versus pressure ( $P$ ) is significantly ( $r^2 > 0.95$ ) linear and just their intercepts and slopes are different. The general equation of the lines can be presented as:

$$e = e_1 - c_c \log p \quad (1)$$

Where  $e_1$  is the intercept of the line and means the void ratio of the sample at unit pressure ( $P=1$ ) and its value affecting from dimension of the pressure and  $c_c$  is the slope of the line (virgin curve) and called compression

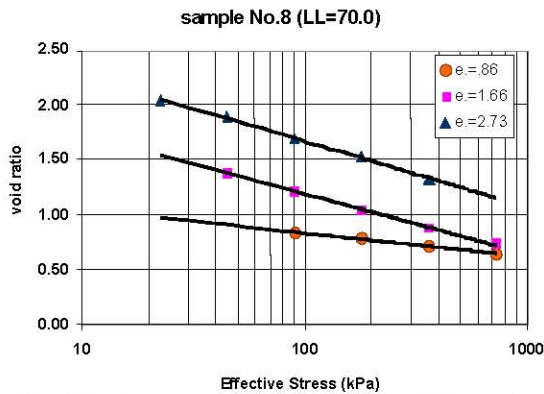


Fig. 1: Virgin curves of sample No. 8 at different levels of void ratio

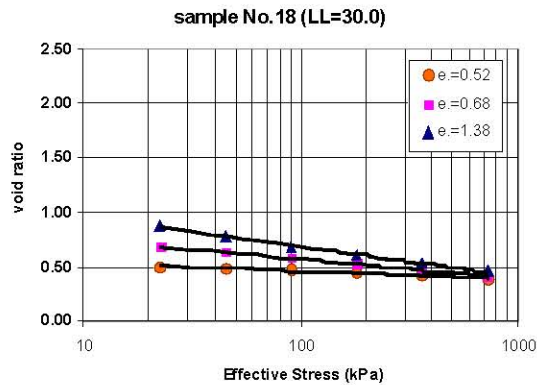


Fig. 2: Virgin curves of sample No. 18 at different levels of void ratio

index. The virgin curves were drawn for all of the specimens and their constant coefficients ( $e_i$  &  $C_c$ ) were determined. The specification of the compression lines of the specimens as well as their liquid limits and initial void ratios were presented as Table 2. It can be seen from Figures 1 and 2 and also Table 2 that compression index of the specimens prepared from a soil sample (having the same liquid limit) with different levels of initial void ratio, are considerably different. The difference in most cases found to be more than three times. Therefore, it can be easily concluded that the single variable empirical equations, using only plasticity characteristics and ignoring structural properties, could not properly estimate the compression index. In addition, the compression index was affected by plasticity characteristics as well.

However, this effect could be negligible in comparison to the effect of initial void ratio (Figures 3 and 4). Therefore it seems that the empirical equations which utilize structural properties such as initial void ratio predict the compression index of soil much better than those utilize only intrinsic properties.

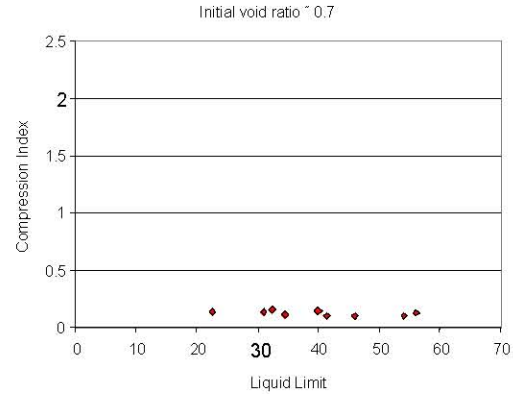


Fig. 3: Compression index of samples with different liquid limit and same initial void ratio

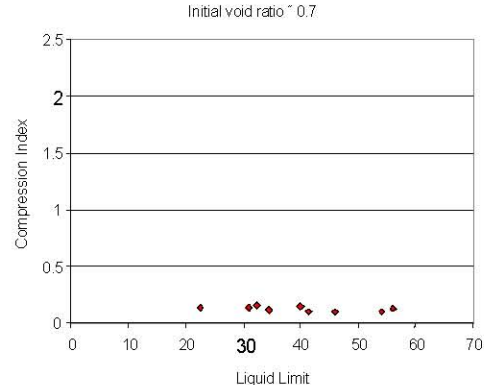


Fig. 4: Virgin curves for samples with different liquid limit and same initial void ratio

### Correlation Between Index Properties and Compression Index

**Index:** It is well-known that compression index is related to different index properties of the soils. In this study, a correlation analysis was made using statistical software, SPSS, to evaluate the correlation of compression index with various physical and index properties of soils. These parameters were clay percent, specific gravity ( $G_s$ ), liquid limit (LL), plastic limit (PL), shrinkage limit (SL), plasticity index, shrinkage index, activity number, maximum dry density ( $\gamma_{dmax}$ ), optimum water content ( $\omega_{opt}$ ), natural dry density ( $\gamma_d$ ), initial water content ( $\omega_0$ ), initial void ratio ( $e_0$ ), void ratio at liquid and plastic limits. The results showed a significant correlation between the compression index,  $C_c$  and most of index properties. But the coefficient of correlation,  $r$ , was around 0.50 for the properties representing the intrinsic properties such as; specific gravity, Atterberg limits and plasticity indices and about 0.92 for those explaining natural state or structural characteristics such as; void ratio, water content and density. Therefore it was concluded that the structural properties are more suitable parameters for estimation of

Table 2: Constant coefficients of the compression lines of the specimens

Specimen No.	LL	$e_0$	$e_1$	$C_c$	Specimen No.	LL	$e_0$	$e_1$	$C_c$	Specimen No.	LL	$e_0$	$e_1$	$C_c$
1a	31	0.50	0.650	0.09	10a	54	0.74	0.887	0.10	19a	40	0.70	0.912	0.18
1b		0.80	0.800	0.17	10b		1.21	1.575	0.32	19b		0.97	1.261	0.25
1c		0.90	1.077	0.22	10c		1.54	2.055	0.45	19c		1.58	1.633	0.36
2a	29	0.60	0.792	0.12	11a	64	0.73	0.984	0.23	20a	31	0.55	0.664	0.08
2b		0.64	0.852	0.15	11b		1.70	2.192	0.49	20b		0.65	0.792	0.14
2c		1.02	1.039	0.18	11c		1.87	2.276	0.51	20c		1.25	1.835	0.41
3a	34.5	0.60	0.749	0.10	12a	57	0.77	.941	0.14	21a	41.5	0.66	0.785	0.10
3b		0.71	0.881	0.12	12b		1.55	1.992	0.45	21b		0.85	1.073	0.21
3c		1.07	1.215	0.24	12c		1.91	2.177	0.49	21c		1.49	1.496	0.29
4a	36	0.55	0.646	0.07	13a	38	0.56	0.692	0.09	22a	24.5	0.49	0.583	0.08
4b		0.81	1.022	0.19	13b		0.88	1.201	0.25	22b		0.52	0.621	0.10
4c		1.13	1.625	0.38	13c		1.21	1.349	0.28	22c		0.91	0.892	0.16
5a	22.5	0.13	0.198	0.08	14a	35	0.53	0.645	0.09	23a	40	0.55	0.651	0.08
5b		0.47	0.544	0.07	14b		0.95	1.248	0.25	23b		0.67	0.864	0.15
5c		0.66	0.800	0.14	14c		1.15	1.348	0.31	23c		1.32	1.331	0.26
6a	32.5	0.57	0.678	0.09	15a	56	0.66	0.801	0.13	24a	31	0.52	0.614	0.07
6b		0.67	0.862	0.16	15b		1.15	1.404	0.27	24b		0.71	0.820	0.14
6c		1.07	1.119	0.18	15c		1.58	1.874	0.44	24c		1.15	1.376	0.27
7a	31	0.52	0.598	0.08	16a	34	0.58	0.751	0.13	25a	30	0.54	0.675	0.10
7b		0.68	0.868	0.17	16b		0.75	0.910	0.19	25b		0.63	0.831	0.18
7c		1.02	1.159	0.21	16c		1.16	1.168	0.20	25c		1.21	1.332	0.31
8a	70	0.86	1.094	0.21	17a	37	0.60	0.722	0.09	26a	34	0.59	0.720	0.10
8b		1.66	2.180	0.51	17b		0.88	1.091	0.24	26b		0.95	1.064	0.16
8c		2.43	2.468	0.60	17c		1.44	1.399	0.27	26c		1.52	1.770	0.34
9a	46	0.68	0.819	0.10	18a	30	0.52	0.617	0.08					
9b		1.00	1.164	0.19	18b		0.69	0.432	0.18					
9c		1.35	1.577	0.26	18c		1.38	1.223	0.27					

Table 3: Candidate empirical models and their statistical indices

RMSE	Coefficient of determination ( $r^2$ )	Equation	Utilized parameters	Model No.
0.068	0.836	$C_c = 0.286e_0 - 0.054$	$e_0$	E-1
0.076	0.848	$C_c = 0.008\omega_0 - 0.044$	$\omega_0$	E-2
0.050	0.820	$C_c = -0.461\gamma_d + 0.883$	$\gamma_d$	E-3
0.116	0.351	$C_c = 0.007LL - 0.043$	$LL$	E-4
0.071	0.841	$C_c = 0.269e_0 + 0.001LL - 0.043$	$e_0, LL$	E-5
0.068	0.858	$C_c = 0.007\omega_0 + 0.001LL - 0.077$	$\omega_0, LL$	E-6
0.058	0.832	$C_c = -0.424\gamma_d + 0.001LL - 0.773$	$\gamma_d, LL$	E-7

compression index,  $C_c$ , compared to intrinsic properties of soil. In addition, among the intrinsic properties, the liquid limit because of its larger coefficient of correlation with compression index was selected as the representative parameter of the intrinsic properties for taking into account in prediction of compression index. Initial values of void ratio, water content and dry density having quite the same coefficient of correlation with compression index can be used alternatively as the representative parameters for statement of natural state or structural properties of soils.

**Development a New Empirical Equation:** As mentioned before, various single and multiple variable empirical equations have been developed by researchers for estimation of the compression index which often suggested for special cases and still are uncertain in application. In this study, in order to demonstrate an

empirical equation for the regions of Iran where the liquid limit of the soil is often less than 75, a statistical study was made. For this purpose, the index properties having strong correlation with the compression index including; liquid limit (representative for intrinsic properties), initial void ratio, initial water content and initial dry density (representatives for structural properties) were used for development of the new equations. Linear regression analyses were performed using mentioned variables, individually to develop single variable equations. Also, two variable equations were developed utilizing combinations of a representative parameter for structural properties ( $e_0$ ,  $\omega_0$ ,  $\gamma_d$ ) and  $LL$ . Table 3 shows the developed single and two variable empirical equations and their statistical indices. Two well-known statistical indices, e.g.,  $r^2$  and  $RMSE$  were used in order to comparison of the performance and precision of the equations.

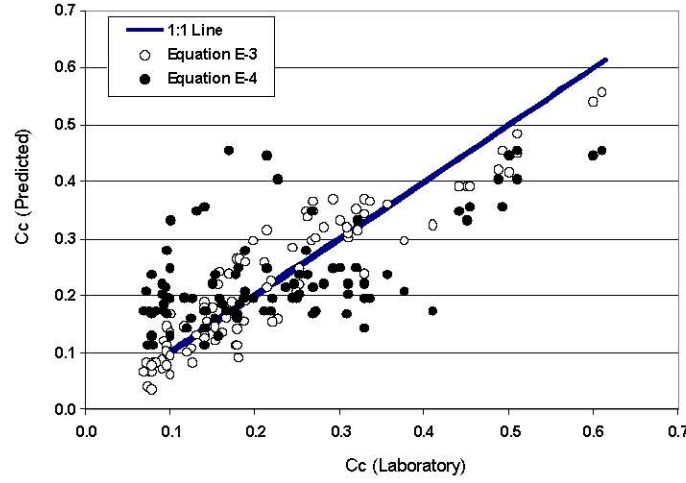


Fig. 5: Scatter plot of data for equations E-3 and E-4

The coefficient of determination ( $r^2$ ) represents the percent of the data that is the closest to the line of the best fit where the highest amount of R squared ( $r^2$ ) shows the best relationship between parameters. The root mean square error ( $RMSE$ ) is a quadratic scoring rule which measures the average magnitude of the error which is defined as following:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (C_{c(est)} - C_{c(det)})^2} \quad (2)$$

where,  $n$  is the number of data points,  $C_{c(est)}$  is the compression index estimated from empirical equations,  $C_{c(det)}$  is the compression index determined in laboratory. Expressing the formula in words, the difference between estimation and corresponding observed values are each squared and then averaged over the sample. Finally, the square root of the average is taken. Since the errors are squared before they are averaged, the  $RMSE$  gives a relatively high weight to large errors. This means the  $RMSE$  is most useful when large errors are particularly undesirable.  $RMSE$  can ranges from 0 to 8 in which negatively-oriented scores, lower values are better. The values of  $r^2$  and  $RMSE$  were 0.35 and 0.10 respectively for the equation utilizing only liquid limit (E-4), whereas, they were found to be quite similar for the other equations and were 0.85 and 0.05 respectively. It means that the model E-4 with the least  $r$  squared and the largest  $RMSE$  is not a reliable model for prediction of the compression index. In order to obtain the most reliable one through the equations having same  $r^2$  and  $RMSE$ ,

more attempts were made using additional laboratory data which had not been used in the developing of the equations. To do this, the amounts of  $RMSE$  were determined for the equations using laboratory data presented in the literature [24] and presented in Table 3. Figure 5 also shows the scatter plot of data for equations E-3 and E-4 with lowest and highest amounts of  $RMSE$  respectively where the further the line is away from the points, the less it is able to explain the strength of the linear association of the model. Table 3 shows the single variable model utilizing initial dry density ( $\gamma_d$ ) provided the lowest  $RMSE$  and considering the fact that the determination of  $\gamma_d$  is very easy in comparison to other parameters listed in Table 3, it was concluded that the model E-3 which is rewritten as equation 3 could be the best model for prediction of the compression index and suggested as a new empirical equation in this study.

In the same manner, Equation 4 was developed for estimation of the intercept of the virgin curve which introduced as the void ratio at unit pressure ( $e_1$ ) in Equation 1.

$$C_c = -0.461 \gamma_d + 0.883 \quad (3)$$

$$e_1 = -1.78 \gamma_d + 3.70 \quad (4)$$

As the amount of  $e_1$  depends on dimension of pressure, Equation 4 determines  $e_1$  whenever dimension of pressure is kPa. Therefore, the general virgin compression curve described by equation (1) can be rewritten as equation 5 considering the equations 3 and 4.

Table 4: Index properties of the soil samples (based on research by Park and Koumoto, 2004) and their estimated and determined compression indices

Soil type	Index properties						Compression index (Cc)					
	LL	$e_0$	$\omega_0$	$\gamma_d$	$e_p$	$\rho_s$	Cc (Laboratory)	Estimated by Empirical equations				
								Determined	Nishida, 1956	Terzaghi and Peck (1967)	Park and Koumoto (2004)	Ozer <i>et al.</i> , (2008)
Kaolinite	66.0	1.377	49.9	1.13	0.90	2.676	0.32	0.55	0.50	0.21	0.38	0.36
		1.626	58.3	1.02	0.90	2.676	0.35	0.69	0.50	0.28	0.45	0.41
		1.776	66.1	0.96	0.90	2.676	0.37	0.77	0.50	0.33	0.49	0.44
Karatsu clay	50.4	0.896	31.5	3.49	0.46	2.618	0.23	0.29	0.36	0.20	0.25	0.25
		1.075	40.7	1.26	0.46	2.618	0.27	0.39	0.36	0.25	0.31	0.30
		1.2	45.4	1.19	0.46	2.618	0.31	0.46	0.36	0.29	0.34	0.33
M1 <sup>a</sup>	72.1	1.388	53.1	1.10	0.98	2.638	0.28	0.56	0.56	0.19	0.39	0.37
		1.694	60.8	0.98	0.98	2.638	0.38	0.73	0.56	0.28	0.47	0.43
		1.851	67.7	0.93	0.98	2.638	0.42	0.81	0.56	0.33	0.51	0.46
M2 <sup>b</sup>	81.7	1.59	56.2	0.99	1.07	2.556	0.33	0.67	0.65	0.22	0.44	0.43
		1.796	65.8	0.91	1.07	2.556	0.4	0.78	0.65	0.28	0.49	0.46
		2.059	78.4	0.84	1.07	2.556	0.45	0.92	0.65	0.36	0.56	0.50
M3 <sup>c</sup>	86.6	1.721	61.2	0.96	1.16	2.616	0.34	0.74	0.69	0.23	0.47	0.44
		2.123	76.9	0.84	1.16	2.616	0.4	0.96	0.69	0.36	0.57	0.50
		2.415	89.2	0.77	1.16	2.616	0.53	1.12	0.69	0.44	0.65	0.53
Ariake clay	78.6	2.37	93.3	0.75	0.79	2.543	0.56	1.09	0.62	0.54	0.65	0.54

Table 5: The studied empirical equations and the values of their RMSE

RMSE	Equations	References
0.379	$C_c = 0.54 (e_0 - 0.35)$	[9]
0.204	$C_c = 0.009 (w_L - 10)^{0.8}$	[12]
0.080	$C_c = 0.302 (e_0 - e_p) + 0.064$	[16]
0.100	$C_c = 0.151 + (0.001225 w_d) + (0.193 e_0) - (0.000258 w_L) - (0.0699 \gamma_d)$	[6]
0.059	$C_c = -0.461 \gamma_d + 0.883$	Proposed in this study

$$e = [-1.78 \gamma_d + 3.7] - [-0.461 \gamma_d + 0.883] \log p \quad (5)$$

Equation 5 states the compression behaviour of the unconsolidated or normally consolidated fine-grained soil which could be estimated using initial dry density of soil samples. As the initial dry density is determined easily in comparison to other index properties such as; void ratio and plasticity indices, equation 3 and 5 estimate the compression behaviour of soil quite easily. Furthermore, unlike the most of index properties which themselves need skills to determine and affected by operator and instrumentation errors, dry density is nearly free from operator and instrument errors. Finally, it can be concluded that the equation 3 estimates the compression index of soils more reliable and easier than the existing equations.

**Verification of the Results:** In order to verification of the proposed equation in this study, statistical analysis was made using data provided in the literature [16]. To do this, the compression index was determined based on proposed in this study and different existing empirical

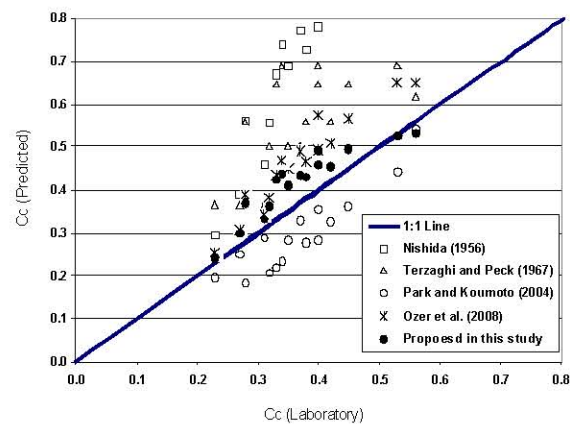


Fig. 6: Comparison of different empirical equations

equations. The index properties of soil samples and their determined and predicted values of the compression index using several existing empirical equations which, are the widely used and recently developed, were presented in Table 4. The initial dry density ( $\gamma_d$ ) of the samples were recalculated using other provided properties.

Then, the root mean square error (*RMSE*) was used as statistical index for comparison of reliability of the different empirical equations. Table 5 shows the studied empirical equations and their values of *RMSE* calculated data presented in Table 4. Also the scattering state of the predicted values of compression index using different equation in related to 1:1 line where the predicted and determined values are equal, presented in Figure 6. It is clearly obvious from the results presented in Table 5 and Figure 6 that the proposed equation in this study with the lowest *RMSE* value is the closest to the 1:1 line and can predict the compression index of soils accurately in comparison to the other mentioned equations. Furthermore, the proposed equation is very simple and uses only dry density ( $\gamma_d$ ) which is obtained easily by measuring of initial weight and volume of the soil samples.

### CONCLUSION

In this study, the effects of physical and index properties of soils were investigated on compression index using different soil samples with a wide range of plasticity collected from different regions of Iran. Using the well-known statistical software, SPSS, correlation and regression analysis were made and a new single variable linear equation was proposed for estimation of compression index of the soil samples. In addition a general compression line equation was developed for prediction virgin curve and compression behaviour of unconsolidated and normally consolidated fine-grained soils. In the mentioned equations, only the initial dry unit weight of the specimens was used as predictor parameter. Also based on the overall results obtained from the laboratory and analytical studies, the following conclusions can be made:

- The whole index properties of soils could be divided into two main groups; *intrinsic* properties which are raised from the mineralogy of the soil particles and *structural* properties which describe the state and distances of particles. Texture (clay, silt and sand content), plasticity characteristics and specific gravity are the most important *intrinsic* properties which are independent from environmental factors and disturbance of soil samples. Unit weight, water content and void ratio are the main structural factors which present the structure and fabric of samples and extremely depend on environmental factors.
- The correlation analysis showed that the most of the physical and index properties of soil have statistically significant correlation with compression

index, however, the coefficient of correlation is different where it was found to be about 0.50 and 0.90 for *intrinsic* and *structural* properties respectively.

- A soil sample with different initial structural condition may have considerably different virgin curve and compression index. Therefore the empirical equations which do not consider at least one structural parameter and use only intrinsic properties could not estimate the compression index, properly.
- The structural properties of soil including; density, water content and void ratio having same correlation with compression index and can alternatively used as a predictor parameter.
- Among the index properties those are easy to determine and less affected by operator and instrument error, are more suitable properties for prediction of other characteristic of soil specially the compression index. Therefore as the proposed equation in this study uses only dry density ( $\gamma_d$ ) which is obtained easily by measuring of initial weight and volume of the soil samples could be reliable equation.

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