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Compression Index of Highly Plastic Clays – an Empirical Correlation

Vinod P.[1] and Bindu J.[2]

Key words

Atterberg limits, compressibility, highly plastic clays, oedometer

Abstract: In view of the time, effort and cost involved in determining compressibility characteristics through odeometer test, it is highly desirable that a predictive equation for compression index is developed. Although several attempts have been made in the past to correlate compression index with index properties as well as initial state parameters of soils, most of the studies are confined to fine-grained soils of low to medium plasticity. This paper presents the results of a study made to characterize the compressibility behaviour of a remoulded, highly plastic, marine soil. The odeometer tests carried out on eighteen samples of this soil indicate that e-log p relationship is linear, the values of compression index being much higher than the reported values. Rigorous statistical analysis of the results obtained has shown that shrinkage index, which is the numerical difference between liquid limit and shrinkage limit, is the most suitable parameter to characterize the compressibility of highly plastic soils. Using the results obtained in the present study as well as those reported in the literature, a generalized compression index equation applicable to soils with a very wide range of plasticity characteristics is also proposed.

Introduction

Compressibility characteristics of soils forms one of the most important parameters required in the design of foundations. The odeometer test is used to determine the compressibility characteristics of fine grained soils and the slope of the straight line portion of the void ratio (*e*) versus logarithm of effective pressure (log *p*) curve, defined as compression index (C_c) is widely used world over to estimate the consolidation settlement of foundations on clays. But, estimation of compression index from laboratory oedometer test requires considerable time and effort. In view of the above and also due to the cost involved in obtaining undisturbed samples, it is highly desirable, at least for a preliminary assessment of settlement of structures, that an empirical correlation for compression index is developed. To properly understand and predict the behaviour of any soil, there can be three levels of investigation in general - the molecular level, the structural level and the phenomenological level (Klausner, 1991 cited by Nagaraj et.al., 1994). Of these, the mathematical formulations at the phenomenological level of investigation, considering soil mass as an entity, is relatively simple and the required soil parameters can be obtained from simple experiments and using less sensitive instruments. Several empirical correlations based on the above approach have been developed in the past to predict compression index. The first well-known correlation is the one presented by Skempton (1944) for remoulded fine-grained soils and is as follows:

$$C_c = 0.007\left(w_L - 10\right) \quad (1)$$

Several correlations were developed by later researchers, each being applicable to a particular soil type. Table 1 summarizes the various compression index correlations reported in the literature (the list is not exhaustive). Initial state parameters as well as plasticity characteristics were used as the independent variables in these correlations. The multitude of equations reported in the literature indicates that none of them can be assumed to have general validity, but that each of them can be acceptable within defined ranges only. This paper presents the results of an experimental investigation carried out to characterize the compressibility behaviour of a highly plastic clay which shows considerable variation in plasticity characteristics. An attempt is also made to arrive at the most appropriate correlation for predicting the compression index of highly plastic clays.

Methodology

Eighteen soils from Kuttanad region in the State of Kerala, India were chosen for the present investigation. The typical soil of the region is soft black or grey marine clay. No in-depth studies on the compressibility behaviour have so far been reported for this highly plastic clay. This paper is an attempt in obtaining and characterizing the compressibility behaviour of remoulded Kuttanad clays.

Apart from odeometer tests, all the soils were tested for their Atterberg limits and grain size

1 Assistant Professor in Civil Engineering, College of Engineering, Trivandrum- 695016, India, E mail: dr_pvinod@rediffmail.com

2 Senior Lecturer in Civil Engineering, College of Engineering, Trivandrum - 695016, India, E mail: binduj7@rediffmail.com

Table 1 Compression Index Equations Reported in the Literature

Equation	*Applicability*	*Reference*
$Cc=0.007(w_L-10)$	Remoulded clays	Skempton 1944*
$Cc=0.035(e_o-0.5)$	Organic soils	Hough 1957**
$Cc=0.009(w_L-10)$	Normally consolidated clays	Terzaghi and Peck 1967
$Cc=0.01(w_n-5)$	All clays	Azzouz et al.1976
$Cc=1.35I_p$	All remoulded, normally consolidated clays	Wroth and Wood 1978
$Cc=0.5I_p\ G_s$	All remoulded, normally consolidated clays	Wroth and Wood 1978
$Cc=0.0046(w_L-9)$	Brazilian clays	Bowles 1979*
$Cc=0.0115w_n$	Organic silt and clays	Bowles 1979*
$Cc=0.208(e_o-0.0083)$	Chicago clays	Bowles 1979*
$Cc=0.156e_o+0.0107$	All clays	Bowles 1979*
$Cc= 0.5(\gamma_\omega/\gamma_\delta)^{2.4}$	All soil types	Herrero 1980
$Cc=0.01w_n$	All clays	Koppula 1981
$Cc=0.01(w_n-7.549)$	All clays	Herrero 1983
$Cc= 0.185[G_s(\gamma_\omega/\gamma_\delta)^2-0.144]$	All soil types	Herrero 1983
$Cc=0.2343\ e_L$	All remoulded, normally consolidated clays	Nagaraj and Srinivasa Murthy 1986
$Cc=0.009(w_L-8)$	Osaka Bay clay	Tsuchida 1991**
$Cc=0.007(I_S+18)$	Remoulded clays	Sridharan and Nagaraj (2000)

*cited by Nagaraj et al., 1994, **cited by Sridharan and Nagaraj, 2000

distribution characteristics. The liquid limit was determined by percussion method as specified by IS: 2720 (Part 5)-1985. The rolling thread method as outlined in IS: 2720 (Part 5)-1985 was used for the determination of plastic limit of the soils. Shrinkage limit was determined by wet pat method (IS: 2720 (Part 6)-1972). While placing the wet soil paste at liquid limit water contents into the shrinkage dish, care was taken to expel entrapped air. The soil was first air-dried and then oven dried at temperature between 105^o and 110^{o}C to prevent cracking due to fast drying. The tests were repeated three times for each sample and the average of the results obtained is reported, the variations between any individual observation from the average being less than 1 percent.

The specific gravity of the soil grains was calculated from the known values of shrinkage limit (using the dry pat method equation). It has been indicated (Narain and Ramanathan, 1970) that drying alters the basic properties of these highly plastic clays. The above-mentioned method of specific gravity determination eliminated any possibility of obtaining erroneous results due to such a change. Grain size analysis was done on all the soils as per IS 2720(Part 4)-1985 by wet sieve analysis for the fraction coarser than 75μm and by hydrometer method for the fraction finer than 75μm. Table 2 presents the various index and physical properties of the soils used in this study. Degree of saturation was taken as 100% for computation of initial void ratio, since all the samples were collected from beneath the water table. Actual values of degree of saturation for all the tested samples were calculated from the in-situ density and initial water content values and the variation was found to be less than 1%. It is also observed from Table 2 that the range of variation of both plastic limit and shrinkage limit is only marginal (29.5% to 50.9% and 14.9% to 28.7% respectively), whereas the liquid limit varies from 70.8% to 276.3 % (nearly four-fold variation) and plasticity index from 34.8% to 235.5%(more than six-fold variation). Figure 1 shows the locations in the plasticity chart of all the samples tested in the present study.

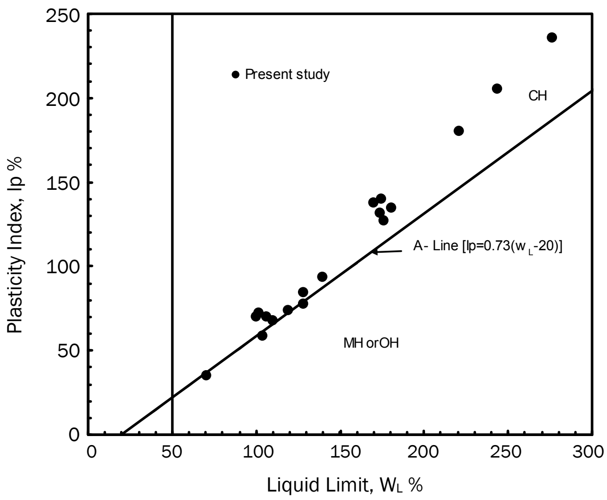

Fig. 1 Position in the Plasticity Chart of the Soils used in the Present Study

Table 2 Properties of the Soils used in the Present Study

Sl.No	Natural water content w_n (%)	Specific gravity G	Liquid limit, w_L (%)	Plastic limit, w_P(%)	Shrinkage limit, w_S (%)	Plasticity index, I_P(%)	Shrinkage index, I_s (%)	Fine sand (%)	Silt size (%)	Clay size (%)	Compression Index Cc
N1	101.6	2.74	119.4	45.7	22.0	73.7	97.4	11.0	56.0	33.0	0.593
N2	94.8	2.77	140.0	46.3	23.3	93.7	116.7	10.0	55.0	35.0	0.851
N3	83.5	2.78	104.0	45.7	28.7	58.3	75.3	11.0	59.0	30.0	0.502
N4	103.3	2.80	128.0	43.4	26.1	84.7	101.9	11.0	60.0	29.0	0.675
N5	64.7	2.71	70.8	36.0	14.9	34.8	55.9	12.0	50.0	38.0	0.515
N6	90.7	2.91	110.0	42.4	23.8	67.6	86.2	9.0	46.0	45.0	0.432
N7	169.3	2.75	221.0	40.8	23.7	180.2	197.3	12.0	46.0	42.0	1.151
N8	136.2	2.75	180.5	45.9	18.5	134.6	162.0	04.0	48.0	48.0	1.033
N9	165.6	2.50	170.0	32.7	18.5	137.3	151.5	8.0	55.0	37.0	0.922
N 10	151.3	2.49	176.5	49.5	15.3	127.0	161.2	10.0	42.0	48.0	0.995
N 11	168.1	2.60	174.4	34.5	22.8	139.9	151.6	7.0	53.0	40.0	1.044
N 12	170.0	2.58	174.0	42.2	18.6	131.8	155.4	10.0	46.0	44.0	0.900
N 13	174.6	2.72	243.9	38.7	18.3	205.2	225.6	11.0	42.0	47.0	1.400
N 14	184.3	2.72	276.3	40.8	21.0	235.5	255.3	11.0	44.0	45.0	1.475
N 15	126.7	2.53	128.1	50.9	21.1	77.2	107.0	01.0	48.0	51.0	0.691
N 16	95.7	2.53	102.0	29.5	17.8	72.5	84.2	02.0	40.0	58.0	0.647
N 17	102.6	2.66	106.2	36.1	28.0	70.1	78.2	01.0	64.0	35.0	0.497
N 18	99.7	2.60	100.2	30.2	25.1	70.0	75.1	01.0	60.0	39.0	0.529

These soils can be classified as clay of high plasticity since most of the plotted points lie on or above the A-line. Table 2 also presents the values of shrinkage index of the tested samples. Shrinkage index (I_S), which is the numerical difference between liquid limit and shrinkage limit, varies from 55.9% to 255.3% (variation being more than four-fold).

As the main part of the present study, conventional odeometer tests were carried out on remoulded Kuttanad clay samples in standard fixed-ring consolidometers using brass rings, 60 mm diameter and 20 mm high. The inside of the rings was lubricated with silicone grease to minimize side friction between the ring and the soil specimen. The soil specimens were hand remoulded in the consolidation ring at their respective natural water contents. Extreme care was taken to prevent any air entrapment in the sample. The ring and the specimen were placed centrally on the bottom porous stone and upper porous stone, and then the loading cap was placed on top. Both the porous stones used were in damped condition to avoid absorption of water from the sample. The consolidation cell was mounted and positioned on loading frame and a vertical deformation dial gauge capable of reading to an accuracy of at least 0.01 percent of specimen height was properly fixed in position. The cell was inundated with distilled water and a seating pressure of 6.25 kPa was applied. After reaching equilibrium, conventional odeometer tests were performed on all the remoulded soil samples. A load increment ratio of one was adopted and each load increment maintained until near equilibrium was attained. Each specimen was loaded to a maximum of 400 kPa.

Results and Discussion

Figures 2 (a) to (c) present the void ratio versus effective pressure (*e*-log *p*) relationship for the eighteen soils tested. It is seen that the *e*-log *p* curves for the remoulded samples tested are approximately straight

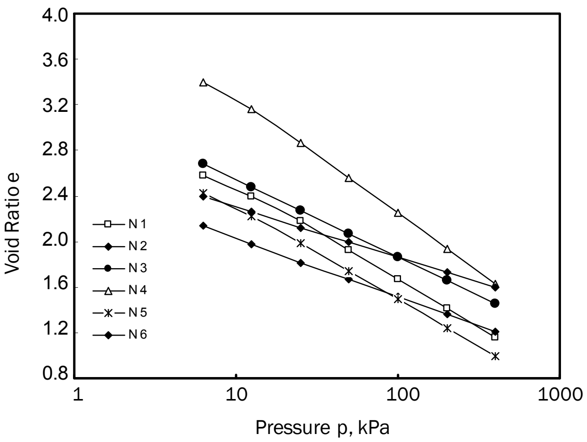

Fig. 2(a) Void Ratio Versus Logarithm of Effective Vertical Pressure of Soils N1 to N6

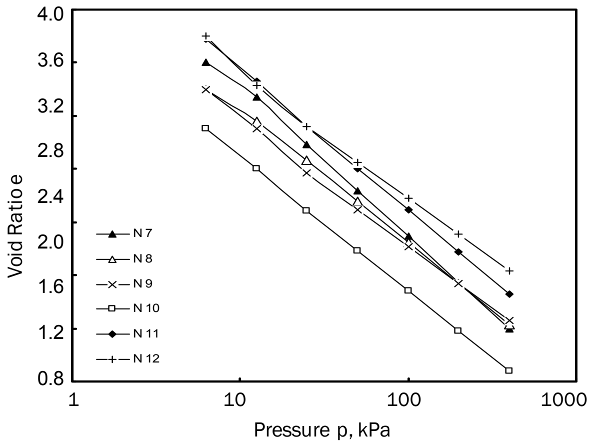

Fig. 2(b) Void Ratio Versus Logarithm of Effective Vertical Pressure of Soils N7 to N12

lines, particularly at higher effective pressures and hence compression index can be taken, for all practical purposes as a constant. Compression indices of tested samples are presented in Table 2. These values are much higher than most of the values reported in the literature (e.g., Burland 1990,

Nagaraj et al., 1994). To bring out the possibility of generalizing the compressibility behaviour of this highly plastic clay and predicting the compression index without the need of elaborate testing, regression analyses of the test results were carried out. Independent variables considered for the regression analyses are same as those reported in the literature by various researchers.

Table 3 presents the relationship of compression index of the remoulded highly plastic Kuttanad clay with index properties such as shrinkage index (I_S), I_S*G, liquid limit (w_L), plasticity index (I_p), I_p*G, void ratio at liquid limit (e_L) and also with initial state parameters such as porosity (n_o), natural water content (w_n), initial void ratio (e_o), and the ratio of unit weight of water to the dry density of soil (γ_w/γ_d) respectively. In all the above analyses except that done with porosity, linear regression yielded the highest value of correlation coefficient. Regression analysis, which yields the best possible correlation/equation for a chosen independent variable can be considered to be only an initial step in the studies related to development of empirical correlations. Use of regression analysis as a tool to estimate accuracy and precision of a correlation is open to criticism (Cherubini and Giasi 2000). A logical comparison of the correlations presented in Table 3,

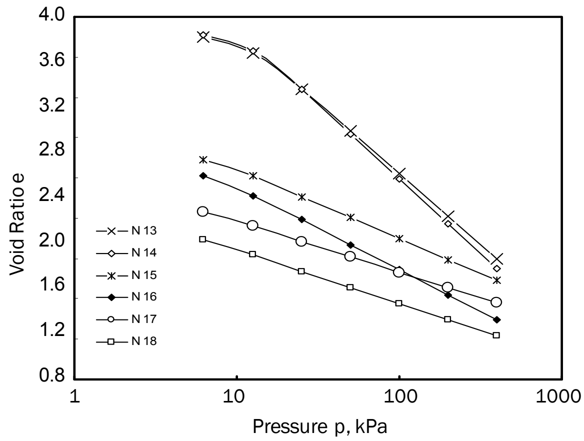

Fig. 2(c) Void Ratio Versus Logarithm of Effective Vertical Pressure of Soils N13 to N18

Table 3 Statistical Analysis of the Correlations Developed in the Present Study

Parameter varied	*Relation*	*Correlation coefficient*	*Cc predicted/ Cc observed*			
			mean	*Standard deviation*	*RD*	*RI*
Shrinkage index (I_S)	$Cc = 0.0055(I_S + 21.2364)$	0.977	1.017	0.112	0.114	0.150
I_S*G	$Cc = 0.002\ (I_S*G + 65.35)$	0.969	1.014	0.134	0.135	0.172
Liquid limit (w_L)	$Cc = 0.0055\ (w_L - 1.8364)$	0.970	1.010	0.131	0.132	0.182
Plasticity Index (I_P)	$Cc = 0.0086\ (I_P + 24.2674)$	0.970	1.019	0.127	0.128	0.172
I_P*G	$Cc = 0.002(I_P*G + 110.55)$	0.963	1.003	0.141	0.141	0.186
Void ratio at liquid limit(e_L)	$Cc = 0.2001\ (e_L + 0.0755)$	0.955	1.020	0.162	0.163	0.210
Porosity (n_o)	$Cc/n_o = 0.0108\ Cc + 0.0018$	0.995	1.059	0.186	0.195	0.266
Natural water content (w_n)	$Cc = 0.0072(w_n - 12.625)$	0.878	1.024	0.184	0.185	0.258
Initial void ratio (e_o)	$Cc = 0.2875\ (e_o - 0.5082)$	0.903	1.024	0.184	0.186	0.257
γ_w/γ_d	$Cc = 0.7045\ (\gamma_w/\gamma_d - 0.4711)$	0.869	1.029	0.186	0.188	0.260

was, therefore, made using an evaluation technique, which simultaneously takes into consideration accuracy as well as precision. Accuracy was estimated by the mean value (μ) while the precision by means of standard deviation (s). A global evaluation of the correlations developed, was carried out by means of two different indices, named ranking distance (RD) (Cherubini & Orr 2000) and ranking index (RI) (Briaud &Tucker 1998) which are defined as follows:

$$RD = \sqrt{\left[1-\mu\left(\frac{C_{c_{calc}}}{C_{c_{meas}}}\right)\right]^2 + s^2\left(\frac{C_{c_{calc}}}{C_{c_{meas}}}\right)} \qquad (2)$$

$$RI = \mu\left|\ln\left(\frac{C_{c_{calc}}}{C_{c_{meas}}}\right)\right| + s\left|\ln\left(\frac{C_{c_{calc}}}{C_{c_{meas}}}\right)\right| \qquad (3)$$

The values of ranking distance and ranking index obtained for the various correlations developed are shown in Table 3. For a good correlation, both these indices tend to zero. Of all the developed correlations, the equation based on shrinkage index yielded the least and most acceptable values for ranking distance as well as ranking index and is given below:

$$C_c = 0.0055(I_S + 21.2364) \qquad (4)$$

Eqn.(4) has mean value very close to unity and the least value of standard deviation when compared to all other correlations. The above equation also has the minimum value of divergence between ranking distance and ranking index suggesting that both accuracy and precision are maximum for the same. The above empirical correlation can be considered quite logical, since liquid limit and shrinkage limit are important parameters controlling the compressibility behaviour. Liquid limit is the extreme limiting water content above which the forces of interaction between particles become sufficiently weak so as to allow easy movement of the particles relative to each other (Warkentin (1961) cited by Narain and Ramanathan 1970). The void ratio at the shrinkage limit can be taken as the limiting void ratio below which volume change would be insignificant. Shrinkage index, which is the numerical difference between liquid limit and shrinkage limit, thus, covers the entire range of water contents only within which any soil would undergo volume change.

It is also worth studying at this stage, the applicability of the correlations for remoulded soils reported in the literature to the highly plastic soil used in the present study. For this purpose, the compression index values of the soils used in the present study were estimated using the correlations listed in Table 1. The mean, standard deviation, RD and RI values for each of the correlations are shown in Table 4. It is seen that ranking distance as well as ranking index values presented in Table 4 are much higher than those obtained in the present study for the correlation based on shrinkage index (Eqn.(4)). The mean and standard deviation values presented in Table 4 are also much less satisfactory than those obtained for Eqn.(4).

It is interesting to note that one of the correlations reported in literature (Sridharan and Nagaraj 2000) also uses shrinkage index as the

Table 4 Comparison of Compression Index Obtained in the Present Study with Predictions Based on Reported Correlations

Equation used	*Reference*	*Cc predicted/ Cc observed*			
		mean	*Standard deviation*	*RD*	*RI*
Cc=0.007(w_L-10)	Skempton 1944*	1.207	0.158	0.260	0.300
Cc=0.035(e_o-0.5)	Hough 1957**	1.251	0.225	0.337	0.379
Cc=0.009(w_L-10)	Terzaghi and Peck 1967	1.551	0.203	0.588	0.565
Cc=0.01(w_n-5)	Azzouz et al.1976	1.528	0.272	0.594	0.590
Cc=1.35I_p	Wroth and Wood 1978	1.760	0.294	0.815	0.722
Cc=0.5I_p G_s	Wroth and Wood 1978	1.745	0.311	0.807	0.721
Cc=0.0046(w_L-9)	Bowles 1979*	0.799	0.104	0.226	0.359
Cc=0.0115w_n	Bowles 1979*	1.836	0.328	0.898	0.773
Cc=0.208(e_o -0.0083)	Bowles 1979*	0.885	0.161	0.198	0.315
Cc=0.156e_o +0.0107	Bowles 1979*	0.680	0.124	0.343	0.580
Cc= 0.5$(\gamma_w/\gamma_d)^{2.4}$	Herrero 1980	2.087	0.585	1.234	0.996
Cc=0.01w_n	Koppula 1981	1.597	0.285	0.661	0.633
Cc=0.01(w_n-7.549)	Herrero 1983	1.493	0.266	0.560	0.567
Cc= 0.185[$G_s(\gamma_w/\gamma_d)^2$-0.144]	Herrero 1983	1.638	0.338	0.722	0.689
Cc=0.2343 e_L	Nagaraj and Srinivasa Murthy 1986	1.169	0.185	0.251	0.291
Cc=0.009(w_L-8)	Tsuchida 1991**	1.576	0.206	0.612	0.579
Cc=0.007(I_S+18)	Sridharan and Nagaraj 2000	1.264	0.139	0.298	0.335

*cited by Nagaraj et al., 1994, **cited by Sridharan and Nagaraj, 2000 independent variable for prediction of compression index of remoulded fine grained soils, but has resulted in a different equation which is as follows:

$$C_c = 0.007(I_S + 18) \quad (5)$$

Different types of soils including natural soils as well as commercially available kaolinite were used in their study (number of data points=10). A close examination of the experimental data used by Sridharan and Nagaraj (2000) in developing the above correlation (correlation coefficient = 0.96) shows that the values of shrinkage index of the tested soils varies from 9.0% to 61.6% only. At the same time, the values of shrinkage index are considerably higher, ranging from 55.9% to 255.3% for the highly plastic soils used in the present study. The experimental data reported by Sridharan and Nagaraj (2000) as well as the results obtained in the present study are shown in Figure 3 along with the shrinkage index based correlations developed in these studies. It can be seen that the slope of the equation

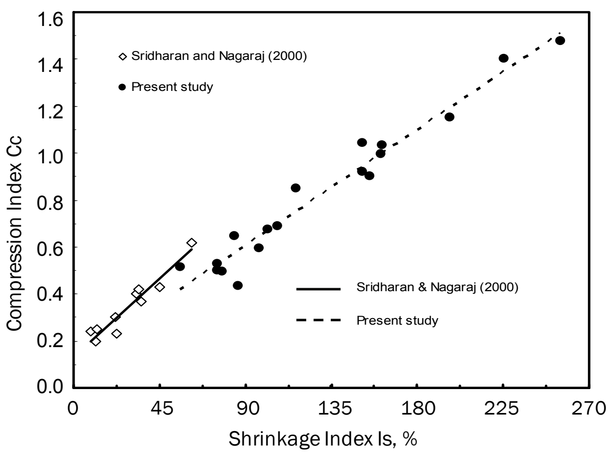

Fig. 3 Comparison of Shrinkage Index Based Compression Index Equations

obtained in the present study is slightly less than that of Sridharan and Nagaraj(2000). Use of Eqn(5) proposed by Sridharan and Nagaraj(2000) if used for highly plastic clays, would result in overestimation of compression index values which may not be acceptable in engineering applications. On the other hand, the use of the Eqn.(4) obtained in the present study would underestimate the compression index values of low plastic soils, but by a lower margin.

A generalized equation for prediction of compression index is developed considering the data reported in the literature (Sridharan and Nagaraj 2000) and those obtained in the present study and is as follows:

$$Cc = 0.0051(I_S + 34.4314) \quad (6)$$

Figure 4 shows the best-fit curve along with the experimental data used for the same. It is seen that the compression index relates well with the shrinkage index over a wide range of values. The ratio of predicted to observed values of compression index yields ranking

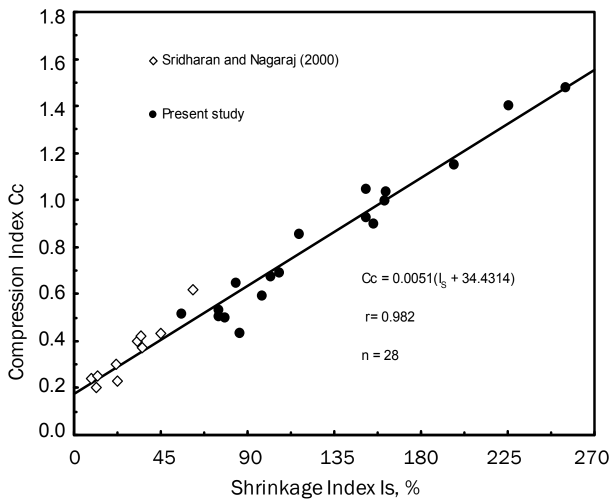

Fig. 4 Generalized Compression Index Equation

distance, ranking index and correlation coefficient values equal to 0.132, 0.173 and 0.982 respectively which may be considered quite satisfactory in engineering applications.

Conclusions

The following conclusions are made from the experimental investigations on eighteen samples of a highly plastic, marine clay. The values of compression index are observed to be much higher than those reported in the literature for most other fine-grained soils. Liquid limit of this highly plastic soil shows about four-fold variation in their values, while plastic limit and shrinkage limit lie within a narrow range. Rigorous statistical analysis of the results obtained has shown that none of the equations reported in the literature yields satisfactory prediction of compression index for this highly plastic soil. The analysis carried out as part of the present study has shown that shrinkage index which is the numerical difference between liquid limit and shrinkage limit is the most suitable generalization parameter to characterize the compressibility behaviour of this highly plastic soil. The analysis has resulted in the following equation with satisfactory values of ranking distance, ranking index and correlation coefficient, (0.114, 0.150 and 0.977 respectively).

$$Cc = 0.0055(I_S + 21.2364) \quad (7)$$

It is suggested that the use of the above equation should be limited to highly plastic soils whereas the use of equation (5) proposed by Sridharan and Nagaraj(2000) should be limited to fine grained soils of low plasticity. Using the results of the present study as well as those reported by Sridharan and Nagaraj(2000), a generalized compression index equation applicable to soils having a very wide range of plasticity characteristics has also been developed:

$$Cc = 0.0051(I_S + 34.4314) \quad (8)$$

The results of study clearly shows that shrinkage index, which takes into account the extreme limits of water content within which volume change takes place, has a definite edge over other index properties in characterizing the compressibility behaviour of clays.

All the oedometer tests carried out as part of the present study were done on samples remoulded at their respective natural water contents. Natural clays may possibly exhibit a different, perhaps larger value of compressibility compared to their remoulded counterpart. This aspect needs examination through extensive field experimentation.

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List of Notations

C_c Compression index

e void ratio

e_o initial void ratio

e_L void ratio at liquid limit

G Specific gravity

I_S Shrinkage index

I_P Plasticity index

n_o porosity

p effective pressure

RD Ranking distance

RI Ranking index

γ_w unit weight of water in kN/m^3

γ_d dry unit weight of water in kN/m^3

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