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Regression Analysis of Soil Compressibility

M. Ayşen LAV, Atilla M. ANSAL
İ.T.Ü. İnşaat Fakültesi,
80626, Ayazağa, İstanbul-TURKEY

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Abstract

A detailed study was carried out to determine the correlations between consolidation properties such as compression index, overconsolidation ratio and various index properties based on test results obtained from 300 soil samples. All of the tests were conducted in the I.T.U. Soil Mechanics Laboratory on samples taken from different construction sites distributed throughout Turkey during the last forty years. Different regression models were utilized and the most suitable relationships with the highest correlation coefficients were established. These developed relationships are compared with similar relationships suggested by various researchers. The proposed correlations appear to be very simple and practically applicable in assessing the consolidation of the soil layers most encountered in Turkey.

Key Words: consolidation, statistics, index parameters, settlement

Zemin Sıkışabilirliğinin Regresyon Analizi

Özet

Sıkışma indisi, aşırı konsolidasyon oranı gibi konsolidasyon özellikleri ile çeşitli indeks özellikleri arasındaki korelasyonları istatistiksel olarak incelemek üzere 300 zemin numunesi üzerinde yapılan deney sonuçlarına dayanan detaylı bir çalışma yürütülmüştür. Deneylerin tümü İ.T.Ü. Zemin Mekaniği Laboratuvarında yapılmış olup numuneler son kırk yıl içerisinde Türkiye'nin çeşitli yerlerindeki inşaat sahalarından alınmış numunelerdir. Çeşitli regresyon modelleri kullanılarak yüksek korelasyona sahip ilişkiler geliştirilmiştir. Bu ilişkiler çeşitli araştırıcılar tarafından kurulmuş benzer ilişkilerle karşılaştırılmıştır. Önerilen bağıntılar oldukça basit ve özellikle Türkiye'de karşılaşılan zemin tabakalarının oturmasının belirlenmesinde kolaylıkla uygulanabilir.

Anahtar Sözcükler: konsolidasyon, istatistik, indeks özellikleri, oturma

Introduction

A vital phase in the selection and design of an appropriate and reliable foundation system is the determination of the types and properties of the soil layers encountered in the soil profile. One of the important issues in this phase is the evaluation of the consolidation of the soil layers under additional loads due to the construction of the planned structures. In a detailed investigation, the conventional approach is to perform subsurface borings to obtain a sufficient number of soil samples which are then tested in the laboratory to obtain the necessary soil properties and estimate the consolidation of the soil layers located in the soil profile. The tests conducted involve the determination of index properties such as water content, dry density, void ratio, consistency limits and consolidation properties such as compression index, swelling index, and overconsolidation ratio.

Depending upon the nature of the encountered soil layers, each will have different index and consolidation properties. Based on laboratory test results, it is possible to evaluate the variation of various soil parameters along the depth of the soil cross-section. In this case the problem is reduced to the determination of the most representative soil parameters that can be used to calculate and estimate the range of possible settlement values with the expected probabilities.

The consolidation is defined as the volume reduction due to the increase in existing confining pressures taking place due to the drainage of pore water. This phenomenon is important mainly for cohesive, fine-grained soil layers and it is a time-dependent process since the rate of drainage of pore water is a function of the permeability of the soil layer.

Conventional consolidation tests are performed mainly to determine (a) the magnitude of the maximum past pressure used to calculate the overconsolidation ratio and (b) the necessary parameters for estimating the magnitude and time of settlement under the additional structural loads.

The overconsolidation ratio is defined as the ratio of the maximum past to present overburden pressure. It is a very important parameter in calculating the settlements and also in determining the shear strength characteristics of the soil layers.

There are various approaches to evaluating the consolidation test results and calculating the settlements. Most of these approaches are based on emprical observations and on accumulated experience. In one of these approaches, the consolidation test results when expressed in terms of the void ratio, e, versus the logarithm of consolidation pressure, $\log \sigma_v$, generally yield a linear relationship, as shown in Figure 1, with a constant slope defined as the compression index, C_c. One advantage of this approach is the availability of emprical methods to correct the laboratory test results and obtain a better approximation of the in-situ field response. Therefore, estimated settlements determined using the corrected compression index are observed to be much more realistic.

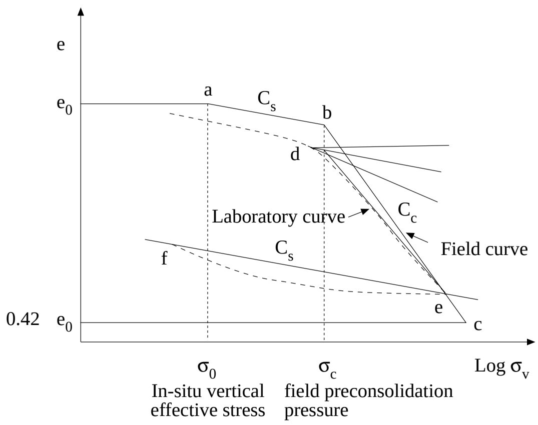

Figure 1. A Typical Consolidation Test Result

However, consolidation tests are expensive and time-consuming. In order to obtain realistic values, special sampling and testing techniques and testing systems are required. It is also essential to conduct these tests with the utmost accuracy and to adopt realistic and suitable procedures to evaluate and interpret the results obtained. However, the group of tests performed to obtain index soil properties are relatively inexpensive and simple. They do not require much time or any sophisticated testing systems.

Under these circumstances, it is very useful in practice to develop emprical correlations for estimating the consolidation properties in terms of index soil properties. These correlations can be utilized to quickly estimate the consolidation settlements of the soil layers and to determine if more detailed and accurate investigation is necessary.

For this purpose, the results obtained with natural soil layers from various parts of Turkey in the last forty years were reviewed. A total of 300 sets of data containing both index and consolidation test results were selected as the database. All of the necessary tests in this database were performed in the I.T.U. Soil Mechanics Laboratories under very similar conditions. The main aim was to develop suitable relationships to evaluate the compression index and overconsolidation ratio in terms of index properties for soils generally encountered in Turkey.

Some Existing Correlations

The statistical evaluation of soil properties has always attracted the interest of geotechnical engineers. The reason for this enthusiasm is the wish to establish correlations between various soil parameters in order to estimate the behavior of soil layers approximately without going through detailed testing and evaluation stages. It is useful to review some of the similar relationships proposed by Nishida (1956), Hough (1957), Sowers (1970), Azzouz et al. (1976), Skempton (1944), Terzaghi & Peck (1967), Cozzolino (1961), Peck & Reed (1954) to evaluate the compression index in terms of index properties.

In most cases, three basic index soil properties, namely, void ratio, water content, and liquid limit, are used to establish expressions to obtain the compression index. As expected, these proposed relationships differ from each other, as can be seen in Table 1, since they are based on different databases.

Table 1. List of Expressions for Compression Index

Proposed Equations	Applicability	Reference
$C_c = 1.15(e_0\text{-}0.35)$	All clays	Nishida, 1956
$C_c = 0.30(e_0\text{-}0.27)$	Silty clays	Hough, 1957
$C_c = 0.75(e_0\text{-}0.50)$	Soils of very low plasticity	Sowers, 1970
$C_c = 0.40(e_0\text{-}0.25)$	All natural soils	Azzous et al., 1976
$C_c = 0.01w_n$	Chicago clays	Osterberg, 1972
$C_c = 0.01(w_n\text{-}5)$	All natural soils	Azzous et al., 1976
$C_c = 0.07(w_L\text{-}7)$	Remoulded clays	Skempton, 1944
$C_c = 0.009(w_L\text{-}10)$	Normally consolidated clays	Terzaghi & Peck, 1967
$C_c = 0.006(w_L\text{-}9)$	All natural soils	Azzous et al., 1976

The Database

The data used in this investigation consist of consolidation and index property test results obtained during the last forty years with samples obtained from different parts of Turkey. All of the tests were performed under similar conditions and using the same technique.

In a study of this nature, it is essential that the tests are conducted under similar conditions. For this purpose, every effort was made to select the test results obtained using the same or very similar testing devices and systems. The consolidation tests utilized in this investigation were performed on mid-size rings with an internal diameter of 60 mm and height of 23 mm. The stress increments followed in all of the tests were the same (25, 50, 100, 200, 400, 1000 kPa) and each load increment was maintained for 24 hours. All of the test results were plotted in the same way as that shown in Figure 1 and the maximum past overburden (preconsolidation) pressure, σ_c, is determined using the graphical method suggested by Casagrande. All of the consolidation tests were also corrected, adopting Schmertmann's procedure to obtain the virgin consolidation line and corresponding compression index.

Each of the data sets used in the analysis consisted of ten soil parameters obtained from various tests. The statistical parameters were calculated for the whole database consisting of 300 data sets, as given in Table 2. The frequency histograms for each soil parameter are shown in Figure 2.

In order to understand the range of variation for soil types used in this study, the plasticity chart shown in Figure 3 was utilized. As can be observed from this figure, the database contained approximately equal numbers of data sets from the four basic groups of soils defined by the chart.

As can be observed from the frequency histograms and from the statistical parameters given in Table 2, for most of the soil parameters it appears realistic to assume a normal distribution. The liquidity index, which is defined in terms of initial water content, liquid and plastic limit, showed the largest coefficient of variation with the value 1.76. Interestingly, the dry unit weight, which is considered physically to reflect some aspects of the liquidity index, showed a relatively small coefficient of variation.

Table 2. Summary of Statistical Parameters for All Soil Properties of All Samples

Soil properties	Units	Mean	Median	Standard Dev.	Sta.Dev.of Mean	Coefficient of variation	Skewness	Kurtosis	Max.	Min.	Range
Initial water content	%	37	33	15	0.86	0.40	1.12	4.14	99	13	86
Liquid limit	%	57	52	20	1.16	0.36	1.14	5.60	166	23	143
Plastic limit	%	31	29	10	0.58	0.33	1.49	7.02	87	16	71
Plasticity index	%	26	23	12.5	0.72	0.48	1.06	5.22	95	5	90
Liquidity index	%	0.24	0.16	0.42	0.024	1.76	0.35	5.50	2.31	-1.29	3.6
Initial void ratio		1.09	0.986	0.439	0.025	0.4	1.47	6.63	3.50	0.45	3.05
Specific density		2.74	2.74	0.06	0.003	0.022	-0.49	2.19	2.83	2.6	0.23
Dry unit weight	tcm	1.36	1.39	0.24	0.014	0.18	-0.31	2.53	1.85	0.62	1.23
Overconsolidation ratio		2	1.6	1.92	0.111	0.86	3.23	18.0	15	0.4	14.6
Compression index		0.336	0.276	0.229	0.013	0.68	3.38	26.2	2.44	0.034	2.402

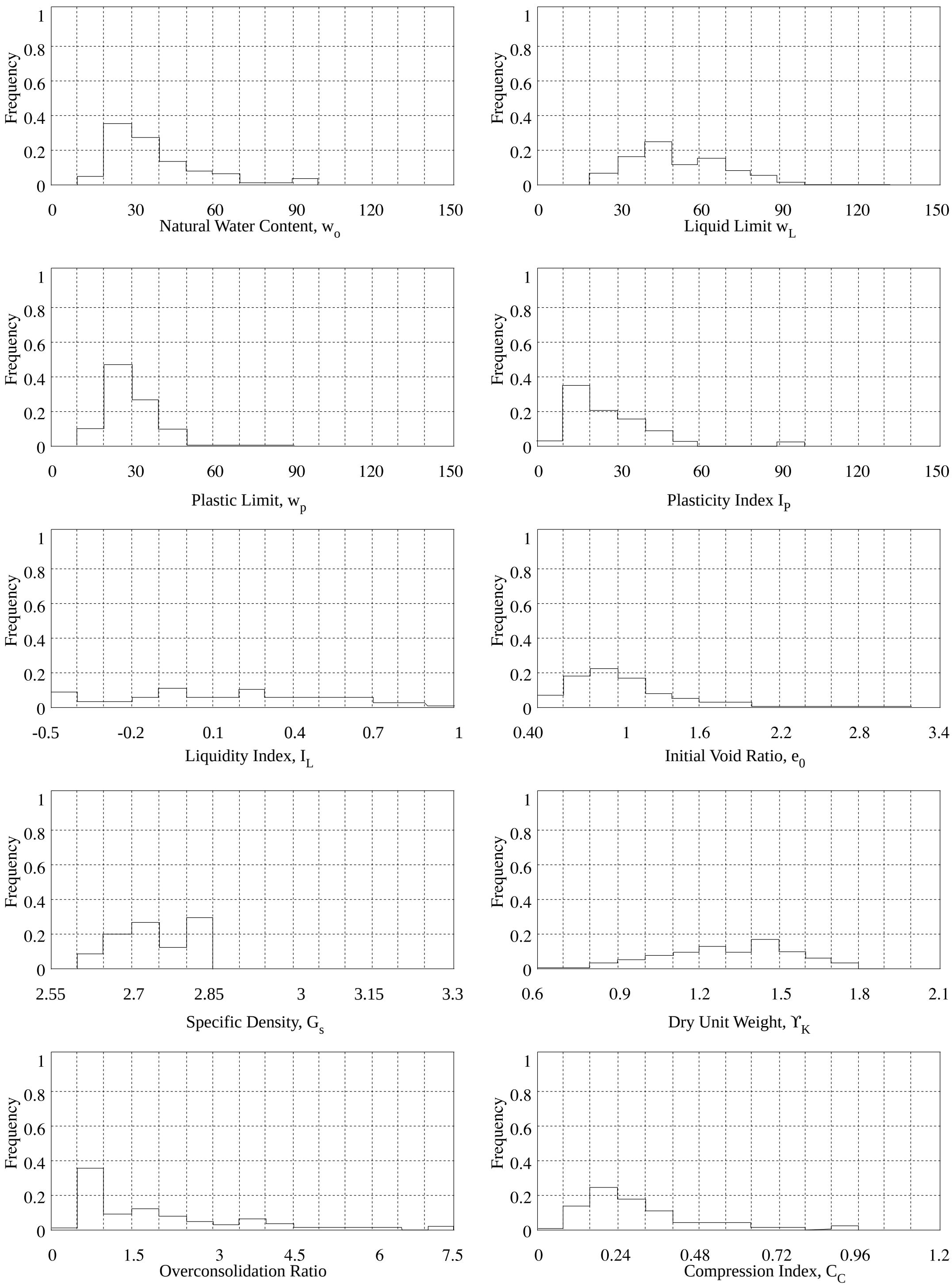

Figure 2. Frequency Histograms for Soil Properties

In the course of the study conducted and after analyzing all the data sets together, it was decided to separate the data into various groups based on properties that are in general considered to be important in evaluating soil behavior. The other purpose was to decrease the variability within each group so that more reliable correlations with better correlation coefficients could be established. For this purpose, the data sets were divided into 9 subgroups according to liquid limit, overconsolidation ratio, dry unit weight, and liquidity index, as shown in Table 3.

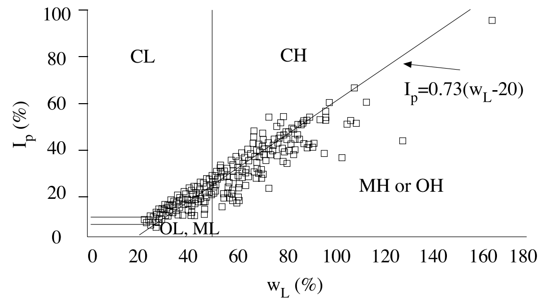

Figure 3. The Distribution of the Data Sets on the Plasticity Chart

Table 3. Definition of Data Subgroups

Subgroup No	Subgroup Property	Data Sets
1	Low plastic soils	139
2	Highly plastic soils	161
3	Normally consolidated	141
4	Overconsolidated	159
5	Dry density $\leq$ 1.3 tcm	118
6	1.3 < Dry density < 1.6 tcm	130
7	Dry density $\geq$1.6 tcm	52
8	Liquidity index < 0.2	152
9	Liquidity index $\geq$ 0.2	148

Prediction of Compression Index

The main purpose of this study was to determine the most suitable correlation for evaluating the compression index in terms of index soil properties based on the database. The first step was the calculation of correlation coefficient matrices for the whole data set and for the subgroups. A lower limit of R $\geq \pm$ 0.5 was adopted for developing various regression models. In this way, it became possible to observe the improvement in the correlations developed due to the adopted subgrouping. The correlation coefficients calculated between the compression index and the other soil parameters for all the subgroups are shown in Table 4.

As can be observed in this table, the dry unit weight and overconsolidation ratio have a low correlation coefficient value for all the soil groups considered in evaluating the compression index. This is interesting because it shows, at least statistically, that the compression index determined in the stage where the soil is in virgin consolidation should be independent of the overconsolidation ratio. The highest correlation coefficient for the compression index was obtained in most of the soil groups with relation to void ratio and dry unit weight. This was expected because dry unit weight is almost linearly related to void ratio.

The correlation coefficients given in Table 4 were determined on the basis of linear regression models. Therefore, in order to improve the calculated correlations, semi-logarithmic and full logarithmic transformations were performed and the related correlation coefficients were calculated. It was observed that in most soil groups the value of the correlation coefficient increased approximately 10-20 %.

The constants in the linear relationships were calculated by utilizing a least-squares approach. A comparison between the relationships proposed by various authors and the ones developed in this study are shown graphically in Figure 4. Some of the previous studies reported with these plots were mainly concerned with small quantities of data and some only with regional soils. One of the major studies conducted in this area was carried out by Azzous, Krizek, and Corotis (1976), where samples from soil layers of different origins, such as marine, aeolian, alluvial, and residual soils, were included in the database, which consisted of 700 data sets. It is very interesting that the relationship proposed to calculate the compression index in terms of void ratio is exactly the same as the relationship developed in the present study. However, the correlation coefficient was lower in the present work. Other similarities were also observed, as can be seen in Figure 4.

A list of possible relationships for estimating the compression index using various index parameters developed in this study is summarized in Table 5. During this study, all possible linear relationships were tried; however, naturally in some of these relationships the correlation coefficients and as a result the reliability of these expressions were low. The equations given in Table 5 are the ones which had the highest correlation coefficient.

Table 4. Correlation Coefficients between Compression Index and Other Soil Parameters for Different Subgroups

Subgroup No →	All natural soils	1	2	3	4	5	6	7	8	9
w_0	0.758	0.744	0.701	0.877	0.646	0.560	0.391	0.468	0.700	0.716
w_L	0.509	0.229	0.355	0.661	0.436	0.238	0.010	-0.117	0.583	0.611
w_P	0.345	0.191	0.113	0.482	0.302	-0.052	-0.130	-0.150	0.580	0.460
I_P	0.540	0.138	0.431	0.676	0.458	0.401	0.104	-0.061	0.447	0.631
I_L	0.485	0.557	0.639	0.491	0.435	0.376	0.302	0.447	0.299	0.240
e_0	0.765	0.800	0.701	0.890	0.654	0.568	0.484	0.425	0.739	0.736
G_S	0.035	0.094	-0.053	0.115	0.035	0.039	0.188	0.023	0.146	0.072
γ_k	-0.746	-0.779	-0.706	-0.862	-0.636	-0.592	-0.452	-0.484	-0.758	-0.736
σ_0	-0.089	0.141	-0.155	-0.310	0.024	-0.126	-0.051	0.357	0.047	-0.078
σ_c	-0.113	-0.068	-0.148	-0.369	0.146	-0.052	-0.126	0.456	0.023	0.031
O.C.R.	-0.100	-0.116	-0.135	-0.308	0.041	-0.095	0.053	-0.075	0.015	-0.023
C'_c	0.928	0.950	0.912	0.938	0.923	0.882	0.871	0.911	0.973	0.906
C_c	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

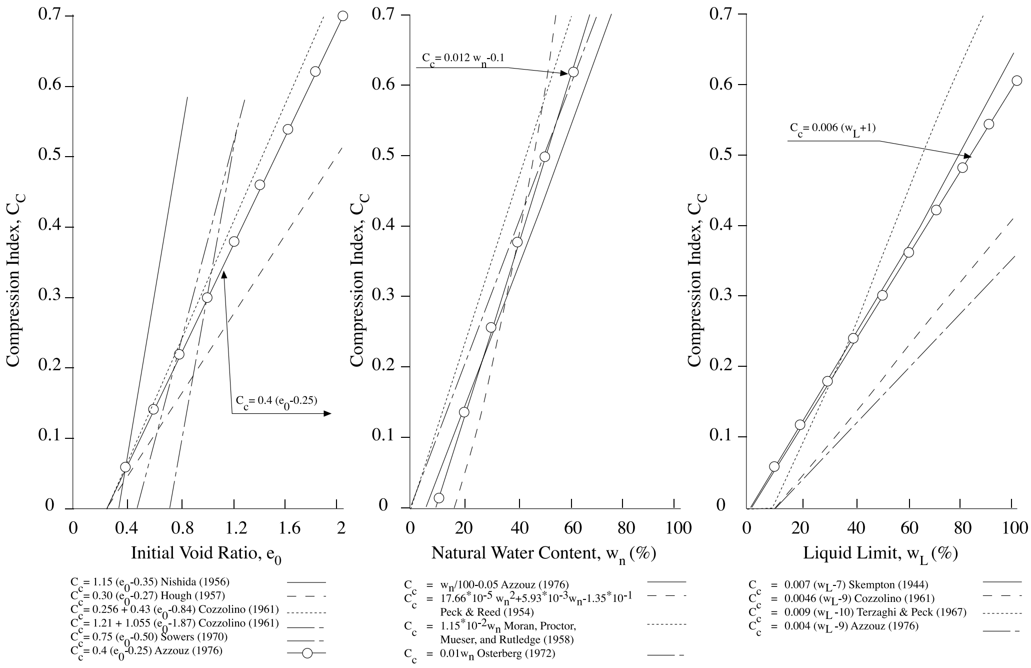

Figure 4. Comparison of Relationships Developed to Estimate Compression Index

Table 5. Summary of Relationships Developed to Evaluate Compression Index for All Soils

Independent Variable	Correlation Coefficient	Regression Equation
Water content, w_n	0.803	$\ln C_c = 1.235 \ln w_n - 5.65$
	0.784	$C_c = 0.479 \ln w_n - 1.367$
	0.758	$C_c = 0.012\ w_n - 0.1$
Liquid limit, w_L	0.509	$C_c = 0.006\ (w_L + 1)$
Void ratio, e_0	0.765	$C_c = 0.40\ e_0 - 0.10$
	0.785	$C_c = 0.485 \ln e_0 + 0.329$
	0.817	$\ln C_c = 1.272 \ln e_0 - 1.282$
Dry unit weight, γ_k	-0.817	$C_c = 0.618 - 0.975\ \gamma_k$

The given developed relationships indicate that the criteria adopted to divide the data into subgroups were not effective in improving the correlation characteristics. This also may be interpreted as a negligible influence on the consolidation phenomena.

It appears from the study conducted that linear expressions with semi-logarithmic transformations lead to better correlations. As shown in Table 6, for some independent variables, even though the calculated relationship changed only very slightly, the correlation characteristics improved significantly.

Table 6. Summary of Relationships Developed to Evaluate Compression Index for Subgroups

Subgroup	Correlation Coefficient	Regression Equation
Low plastic	0.762	$C_c = 0.326 \ln w_n - 0.838$
	0.820	$\ln C_c = 1.43 \ln e_0 - 1.19$
	0.744	$C_c = 0.012\ w_n - 0.086$
	0.800	$C_c = 0.407\ e_0 - 0.094$
	0.814	$C_c = 0.317 + 0.338 \ln e_0$
	0.812	$C_c = 0.556 - 0.769 \ln \gamma_k$
Overconsolidated	0.721	$C_c = 0.481 \ln w_n - 1.376$
Normally consolidated	0.877	$C_c = 0.012\ w_n - 0.098$
	0.890	$C_c = 0.43\ e_0 - 0.122$
	0.661	$C_c = 0.007\ w_L - 0.029$
Liquidity index ≥ 0.2	0.716	$C_c = 0.012\ w_n - 0.085$
	0.736	$C_c = 0.405\ e_0 - 0.064$

Conclusions

A database consisting of 300 data sets containing index and consolidation parameters was used to conduct a statistical study to determine suitable correlations for estimating consolidation response. For this purpose, various linear regression models were adopted and a parametric study was carried out in order to obtain the most suitable and practically applicable relationships. It was observed that the void ratio, water content, liquid limit, and dry unit weight yielded sufficiently reliable correlations.

References

Azzous, A.S., Krizek, R.J., and Corotis, R.B., "Regression Analysis of Soil Compressibility", Soils and Foundations, 16(2), 19-29, 1976.

Cozzolino, V.M., "Statistical Forecasting of Compression Index", Proc. of the 5th Int. Conf. on Soil Mechanics and Foundation Engineering, Paris, 1, 51-53, 1961.

Hough, B.K., Basic Soils Engineering, The Ronald Press Company, New York, 114-115, 1957.

Nishida,Y., "A Brief Note on Compression Index of Soils", Journal of Soil Mechanics and Foundations

Division, ASCE, 82, SM3, 1027-1-1027-14, 1956.

Peck, R.B. and Reed, W.C., Engineering Properties of Chicago Soils, Engineering Experiment Station, University of Illinois, Bulletin 423, 1954.

Skempton, A.W., "Notes on the Compressibility of Clays", Quarterly Journal of Geological Society of London, 100, 119-135, 1944.

Sowers, G.B., "Introductory Soil Mechanics and Foundations", The Macmillan Company, Collier-Macmillan Limited, London, 3rd Edition, 102, 1970.

Terzaghi, K. and Peck, R.B., "Soil Mechanics in Engineering Practice", John Wiley & Sons Inc. New York, 1967.