Compressibility Relationships for Soils in Puerto Rico
Correlaciones de Compresibilidad para Suelos en Puerto Rico

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Presented at Soil and Rock America,
12th Panamerican Conference on
Soil Mechanics and Geotechnical Engineering,
Cambridge, Massachusetts, June 2003

Abstract
An extensive database surpassing 400 consolidation tests from alluvial and residual soils on the island of Puerto Rico was reviewed. Data included compressibility parameters (based on $C_c/(1 + e_0)$ and Atterberg Limits. Maximum past pressures were determined and overconsolidation ratios were calculated. Relationships for compressibility versus water contents, also considering plasticity and overconsolidation ratio were developed. Data from alluvial soils were treated separately from residual soils. These relationships are proposed for preliminary settlement computations in alluvial soils on the island and general geotechnical practice.

Resumen
Este artículo presenta los resultados del análisis comparativo llevado a cabo con los datos de ensayos de consolidación recopilados en una base de datos de más de 400 puntos. Estos ensayos se llevaron a cabo en suelos residuales y de origen aluvial en la isla de Puerto Rico. Los datos comprenden parámetros de compresibilidad del suelo, basados en $C_c/(1 + e_0)$, y limites de Atterberg. La máxima presión pasada o presión de preconsolidación fue determinada, con lo que se obtuvo la razón de sobreconsolidación de cada una de las muestras. Se desarrollaron correlaciones entre la compresibilidad del suelo y su contenido de humedad natural, considerando parámetros como la plasticidad y el grado de sobreconsolidación. Datos correspondientes a suelos de origen aluvial son tratados por separado de los puntos correspondientes a suelos clasificados como residuales. Estas correlaciones son propuestas para el cálculo de estimados preliminares de asentamientos en suelos aluviales en la isla de Puerto Rico y en la práctica profesional en general.

1 INTRODUCTION

While the island of Puerto Rico is small (100 by 35 miles), it has a diverse geologic scenario. The age of alluvial deposits varies widely. The effects of desiccation vary throughout the area. The origin of alluvial deposits ranges from derivatives of limestone, to transported remnants of volcanic rock. Residual deposits are extensive, and the intensity of weathering differs widely. The residual deposits are also derived from weathering of many sedimentary rocks, to weathered igneous material; cementation varies. There are also residual deposits from sedimentary soils, that is, granular deposits weathered in situ to residual soil. Moreover, large changes occur over short distances. Within a two-mile radius, one can find Quaternary peats and organic clays, residual limestone deposits, and weathered volcanic remnants; it is not unusual to find residual and alluvial soils on the same project.

The database that is presented has been compiled over the past 25 years, approximately. In all cases, the data were obtained by the authors in a private laboratory dedicated to geotechnical engineering practice. As might be expected, the database is not of research quality due to changes in personnel and testing procedures over time.

The tests presented were all taken to a final load of 16 tons per square foot (tsf). A load increment ratio (LIR) of 1 was generally used on all tests, with a starting load of 0.125 tsf. In most cases, an unload-reload cycle was started at 2.0 tsf, down to 0.25 tsf, then up to the final load. The majority of the tests include Atterberg limits. The data has been qualified as alluvial or residual, according to origin of the specimen. In all cases, maximum past pressure was calculated using the Casagrande construction. Specimens were usually extracted from Shelby tubes using threaded or motorized hydraulic sample ejectors.

The compressibility parameters discussed herein are the compression index (C_c), the compression ratio (CR), where CR = C_c / (1+e_0) and the recompression ratio (RR) where RR = C_r / (1+e_0) and C_r is the recompression index. Use of CR and RR has several advantages in private geotechnical engineering practice: the assumption of a value for the specific gravity of the material is not necessary for preliminary calculations; compressibility graphs of strain versus log of effective stress can be used to easily compare and distinguish different soils, and the parameter of interest, strain, is directly obtained. In all cases where it is presented, recompression ratio RR was calculated using the strain at the last unloaded point and the midpoint strain at the start of unloading.

The intent of the authors is to present the data and to suggest possible engineering correlations that can be used for preliminary settlement and compressibility estimates. The wide scatter in data is emphasized, which also emphasizes the possibility of wide variation in compressibility parameters within the same deposit and therefore the need for extensive testing for definitive calculations at any site.

2 PRESENTATION OF DATABASE

The database is not presented herein due to space considerations, but it is available at www.geoconsult-inc.com or www.geoconsult.us. Additions to the data can be made, and presentations and review of existing or expanded data is encouraged. The information included in the database is: approximate location of the project, project name, boring label (specimen source), sample depth, sample qualification (alluvial, residual or fill), water content, Atterberg limits (when taken), initial void ratio (when available), compression index, compression ratio, recompression ratio, unit weight (when available), in situ stress, maximum past pressure, coefficient of consolidation, and overconsolidation ratio.

The raw data used for this study includes more than 400 consolidation tests corresponding to soil specimens across the island. All consolidation tests were performed in a 1-D consolidation oedometer device. For alluvial soils, the data consists of 356 consolidation tests. While residual soils have also been presented, the database contains only 38 data points. However, the difficulties associated with standard testing methods on this type of soil, makes it impossible to obtain a good correlation for compressibility parameters, impeding the formulation of any conclusion in this regard. Nevertheless, some useful conclusions can be drawn from the analysis. The database is constantly expanded and data continues to be entered. Properties such as coefficient of secondary compression $C_{\alpha\varepsilon}$ for organic soils are to be added, as well as the completion of missing unit weight data, and coefficient of consolidation (c_v). These are not further discussed in the present article since the data is still being reviewed.

3 DATA PROCESSING

The purpose of the analysis presented in this paper was to find a fast and simple empirical relationship that could be used to obtain estimates of the compressibility of soils due to loading, represented by CR, RR, and maximum past pressure (MPP). Initial data processing focused on correlation of CR with the water content, as suggested in Terzaghi and Peck (1967) and Terzaghi, Peck and Mesri (1996). Although all the available data points were reviewed for this study, at various stages of the analysis some tests were removed for reasons such as: (1) incomplete data (no Atterberg Limits); (2) Liquid Limit or water content above 100; and, (3) water content greater than Liquid Limit. While there might be some locations with underconsolidated soils (OCR<1), specialized sampling techniques that are necessary to obtain reliable data were not used and thus any results showing underconsolidated soils were generally considered unreliable.

3.1 Water content correlations

Considering that the compression of soils is caused by water being squeezed from voids within the soil structure as the stress acting is increased, and that the rate at which this compression increases with respect to increments of stress is represented by the CR, it seems logical to try to correlate this parameter with the natural moisture content of a soil. **Figure 1** shows the results of plotting CR versus water content (W_n) for all selected data points. An acceptable correlation is achieved for soils of alluvial origin, although scatter is somewhat significant. For residual soils however, this correlation does not yield reliable results.

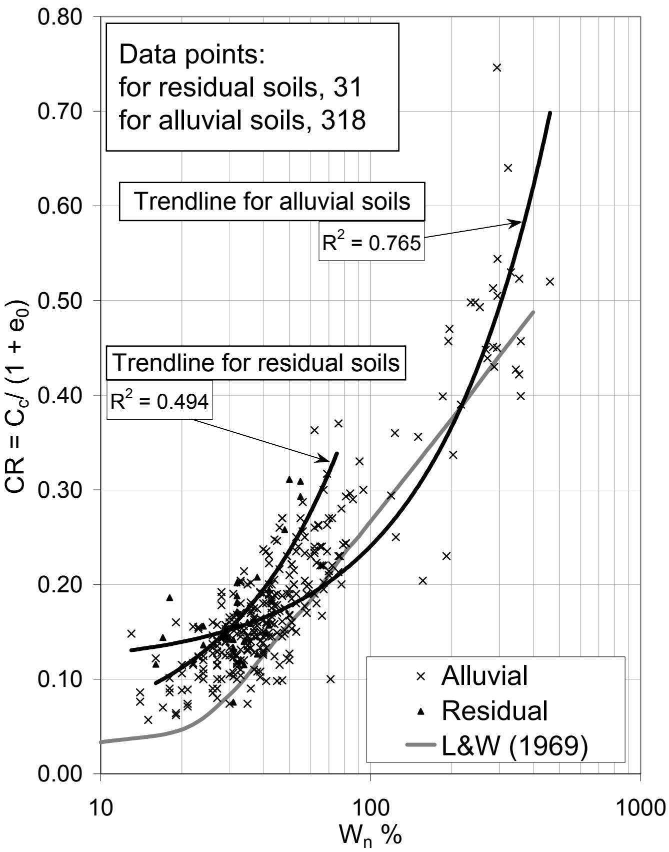

Figure 1 Compression Ratio vs. Water content

There is a significant difference in the virgin compression characteristics of residual and alluvial soils with respect to moisture content. This indicates the complex nature of residual soils and the difficulties encountered when their mechanical behavior is studied using standard methods developed for depositional soils. Factors such as sample disturbance will significantly alter the behavior of the soil specimen in the oedometer compared to its true performance in the field. The effects of such disturbance will generally degrade the mechanical characteristics of the soil, thus making it appear less compressible (lower CR) but with a lower maximum past pressure or yield stress: the reality is that the soils will be more compressible after bonds are broken (greater CR), yet they will retain their cementation and apparent maximum past pressure to a higher stress than the consolidation tests would indicate. Another important point, when trying to formulate correlations of virgin compression for a residual soil, is to consider that the compression index increases but later decreases as the load passes beyond the yield stress. This produces a curved virgin compression line in a semi-logarithmic strain versus stress plot. The reason for this behavior is the structured nature of the soil particle, provided by cementation. This fact makes it difficult to determine a unique value for CR or Cc of a soil that exhibits this behavior. Adding to the problem, the oedometer test does not provide a good resolution in cases of materials of this type, for which a constant rate of strain consolidation test would be more appropriate, as pointed out in Ladd et al. (1999).

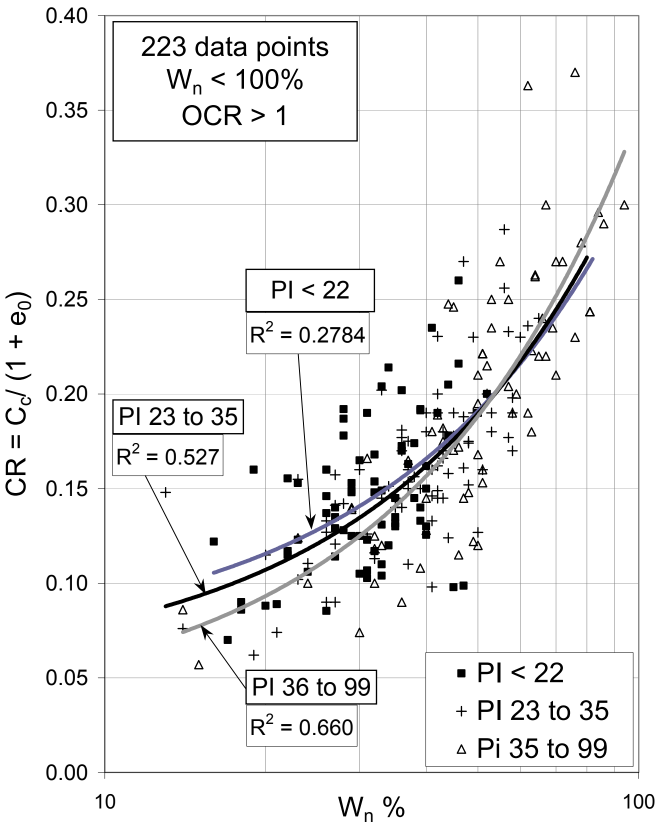

Figure 2 CR vs. W_n. Grouped by PI

For comparison purposes, the average CR versus Wn plot that is shown in Lambe and Whitman (1969) is presented on Figure 1.

By segregating the data for the alluvial material grouped by specimens with similar plasticity index (Figure 2) and similar liquid limit (Figure 3) a trend can be observed that indicates that the natural moisture content correlation is more applicable to higher plasticity and higher liquid limit materials. This is observed by examining the coefficients obtained for the trend lines of three groups in each category. This observation can be explained by the fact that more plastic material and specimens with higher liquid limit will have a larger capacity to hold water due to the larger specific surface area of the soil particles. The consolidation parameters in these soils will therefore be more influenced by the displacement of water from the particle than from elastic and/or plastic deformation of the particles themselves. Therefore, there is a better correlation with moisture content. Residual soils were not included in these plots. It is considered that the use of Atterberg limits as index properties for these soils is a practice than needs to be revised since it involves a high degree of remolding of the soil sample, which dramatically alters the structure nature of the residual soil particle. The results are also highly dependent on the energy used in the remolding process.

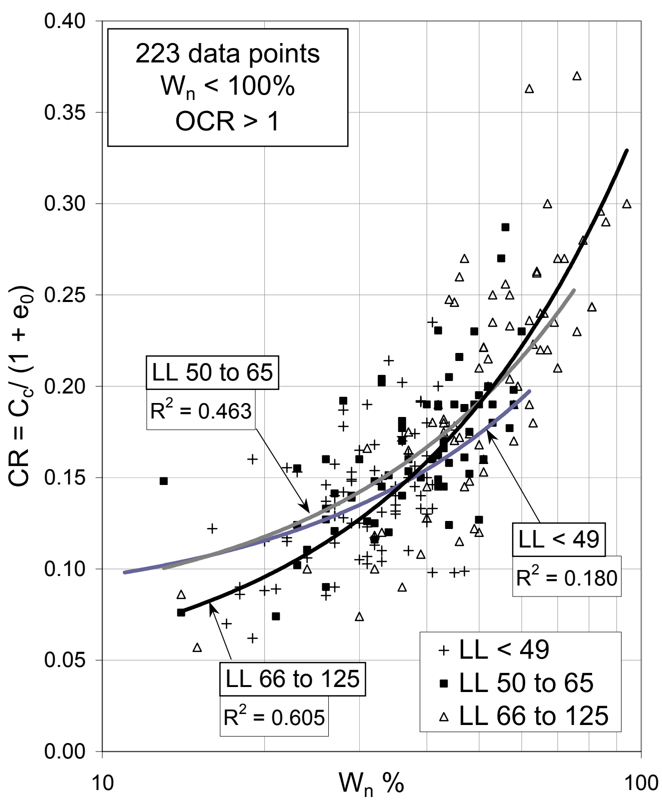

Figure 3 CR vs. W_n. Grouped by LL

3.2 Correlation of liquidity index and maximum past pressure

The manual DM-7 (1982) presents a graph of Liquidity Index versus Maximum Past Pressure, including the effect of soil sensitivity. The sensitivity of soils was not measured in any of the tests but, based on local experience, it can be said that most soils on the island have low sensitivities. The maximum past pressures were plotted against the liquidity indices, as shown on Figure 4. It was attempted to separate the data according to water contents, as shown on Figure 5, on the basis that the amount of overconsolidation affects the water content. A trend can be noted with respect to increasing liquidity index, although scatter is so wide that the data cannot be reasonably utilized in this manner. The only conclusion that can be drawn from the referred plots is that the correlation proposed in DM-7 is generally overly conservative for soils with moisture content larger than 35%.

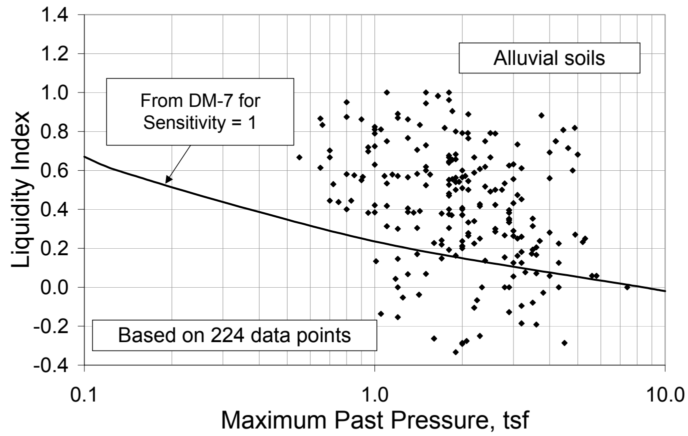

Figure 4 LI vs. Maximum past pressure

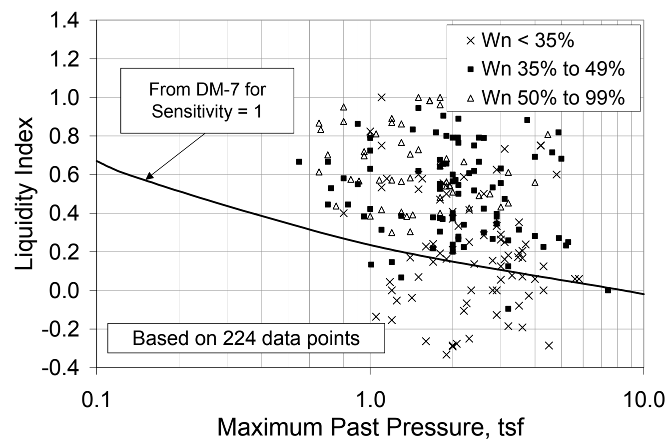

Figure 5 Liquidity index vs. Maximum past pressure

3.3 Compression ratio versus recompression ratio

For all tests where CR and RR were obtained, their corresponding ratios were calculated. Values exceeding 20 were rejected since they surpass the characteristic values of 5 to 10. Using 275 data points for alluvial soils, the average ratio of CR to RR is 9.8. Only twenty residual data points were available for review; their CR/RR ratio was 12.0. However, the nature of this ratio is very doubtful since the maximum past pressure (yield stress, in correct terminology) of a residual soil appears to be less than the actual yield stress, due to disturbance of the soil sample. Based on this, the ratio is expected to be greater than is obtained in the data. This result can be expected, since the first cycle of recompression of a residual soil in an oedometer test reflects the degree of cementation of the soil, rather than an elastic deformation such that is observed on deposited soils.

4. CONCLUSIONS

As stated in Lambe and Whitman (1969), "relationships between compressibility characteristics with Atterberg Limits should be used as intended – only as an estimate of virgin compression characteristics and never as a substitute for results of actual tests." The data herein presented has wide variability, as expected in an intricate geologic scenario, and as would also be expected in an environment where personnel change with time and where levels of training vary. The comparison between CR and Wn only indicates trends that can be used in practice for initial estimates of compressibility in the virgin compression range.

Based on the results obtained from the analyses presented here, the following correlation is proposed for alluvial soils:

$$CR = 0.001\, W_n + 0.114 \qquad (1)$$

For recompression situations, a value of one-tenth the CR value can be used. As an initial estimate of maximum past pressure, the liquidity indices can be carefully used based on the correlation proposed in DM-7. This practice will generally result in a safe estimation of the soil stress history. From this estimate, preliminary settlement calculations using RR and CR can be made. The need for actual compressibility testing is emphasized. But, empirical correlations for estimating parameter values as a function of index properties can be "a valuable, though perhaps neglected, technique" (Ladd et. al., 1977).

The formulation of this type of correlations for residual soils is yet to be proven. Among the factors that make this task such a difficult one are: the difficulty to successfully retrieve and test a truly undisturbed sample, so that the true mechanical properties of the specimen are measured; the lack of an effective methodology to truly measure index properties of a soil of this nature; and the fact that the behavior of this type of soil exhibits a non-constant compression index.

Current feasible techniques of sample retrieval used in professional practice induce excessive disturbance to the residual soils. This greatly impacts the results obtained in a test. Techniques such as block sampling can help solve this problem but are much too expensive to use as a standard method in professional practice. The use of radiography could be implemented in order to evaluate less disturbed zones within the sampling tube from which to extract the specimen. In Puerto Rico, unfortunately, this technique would be very expensive to implement.

The benefits of using constant rate of strain consolidation tests on residual soils should be evaluated. This practice should disclose the true variability of the rate of compression of this type of soils.

It is hoped that others will add to the existing data, conduct additional reviews and continue to build on the seed data that is herein discussed.

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