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Evaluation of Pre-consolidation Stress Determination Methods

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ABSTRACT: Pre-consolidation pressure provides valuable information about soil behavior and, specifically, settlement under an induced load. Soil is expected to have less settlement before its pre-consolidation pressure and much more settlement after that point. The pre-consolidation pressure and the compressibility of the soil can be determined from the results of a one dimensional consolidation test. Different methods have been developed to obtain the accurate pre-consolidation pressure from one dimensional consolidation test data. This paper presents and discusses the results of the one-dimensional consolidation test data from an extensive testing program. The test specimens used were obtained from multiple borehole locations and were extracted using Shelby tube samplers. The focus of this paper is the comparison of three pre-consolidation stress determination techniques, which were performed on each specimen of the large sample pool. The methods used were the Casagrande method, strain-energy method, and intersecting tangent method. The implementation of these methods will be evaluated. In addition, the subjectivity of each method will be addressed. The final results of the techniques will then be compared and contrasted.

INTRODUCTION

Consolidation testing is very common, yet the level of uncertainty pertaining to determining pre-consolidation pressure results remains relatively high. Graphical interpretation of results can greatly impact the reported pre-consolidation pressures, and thus will have a significant impact on geotechnical design.

The purpose of this paper is to present three different methods of obtaining pre-consolidation pressure. The one-dimensional consolidation test (ASTM D2435) results of an extensive testing program are presented, and all three methods were used on each specimen. The trends that each method developed in comparison with the others are discussed. The impact of human subjectivity on data interpretation will also be considered. Conclusions and recommendations for future consideration when using the methods are presented.

BACKGROUND

The Casagrande method is both widely known and the most popular method. Pre-consolidation pressure, according to Casagrande (1936), is the "largest overburden in which the soil had been overconsolidated". The method he proposed is based on the semi logarithmic relationship between void ratio and vertical effective stress. This method was developed from two conclusions drawn by Casagrande (1936): (*i*) the disturbance by unloading during sampling, etc. does not obliterate or seriously distort the impression created by the largest previous load; (*ii*) the shape of the recompression curve before pre-sconsolidation pressure and the shape of the unloading–reloading curve are similar, and their relations to the virgin compression line are also similar.

The tangent method is an even simpler method used by engineers for estimating the preconsolidation stress. This method is extremely simple to perform and "defines another 'most probable' pre-consolidation pressure" (Holtz, 1981).

The strain-energy method (Becker et al. 1987) also uses Casagrande's (1936) first conclusion and the conclusion of Mesri and Choi (1985) which states that a unique relation between end of primary consolidation void ratio and effective stress exists. As for the term "similar" in Casagrande's second conclusion, Becker et al. (1987) assumed a linear relation between total strain energy E and the effective stress p (E–p) for the recompression portion directly from the laboratory recompression curve without considering the unloading–reloading portion of the tests (Wang and Frost, 2004). Unlike Casagrande's method, which focuses more on the local properties (the largest curvature) around the pre-consolidation pressure, the Becker et al. energy method has adopted the average slope of the recompression curve before the pre-consolidation pressure. The energy method is relatively new, more inclusive, and conceptually very promising.

SAMPLING METHOD

All the specimens tested were sampled using a standard Shelby tube approximately 7.6 cm. (3 in.) in diameter and approximately 1.5 meters (5 ft.) long. Specimens from borehole B1 and B2 were sampled from Warrensburg, Missouri. The geology of the area consists of alluvial valley-fill on Desmoinesian Pennsylvanian marine strata, which is primarily comprised of shales and thin limestones. The equipment used was a CME 850 track rig and a Failing 1500 drill rig. The borehole B3 specimens were obtained from St. Charles, Missouri. The bedrock for this area is formed of the St. Louis Limestone (Upper Mississippian, Meramecian). This formation is a dark gray, finely crystalline to lithographic, thin to medium-bedded to massive limestone, which spreads all over to the northwest of the Missouri river. The equipment use in this bore was a Failing 1500 drill rig. The specimens from borehole B4 were taken in New Florence, Missouri. This area, near the Missouri River, is covered by alluvial deposits including silt and clay.

ANALYSIS

Methodology

The method of determining the pre-consolidation pressure of a specimen according to Casagrande requires the use of a void ratio versus the logarithm of pressure plot. The first step is to locate the point of minimum radius (or point of maximum curvature) on the consolidation curve. No specific means of doing this is prescribed. Many engineers simply use their own judgment of eye to achieve this while others plot the consolidation curve in drafting software and obtain the point of maximum curvature from the software. Secondly, a horizontal line is drawn through the point of maximum curvature. Thirdly, a line tangent to the consolidation curve is drawn at the point of maximum curvature. The angle formed by the tangent line and the horizontal line is then bisected. The straight portion of the virgin compression curve is then extended until it intersects the bisecting line. The stress that corresponds to that intersection point is the determined pre-consolidation stress.

The tangent method of determining the pre-consolidation pressure of a specimen requires the use of a void ratio or strain versus the logarithm of pressure plot. Firstly, a linear trend line is drawn through the re-compression portion of the consolidation curve. Secondly, a linear trend line is drawn through the virgin compression portion (virgin line) of the curve. The stress that corresponds to the intersection point of these two trend lines is the determined pre-consolidation stress.

The strain-energy method of determining the pre-consolidation pressure of a specimen requires the use of a cumulative energy versus the effective stress plot. Aside from the parameters being plotted, the graphical determination of the pre-consolidation stress is identical to that of the intersecting tangent method described above.

Subjectivity

The results from those graphical methods are highly dependent upon the data interpreter. In order to determine the effects of human subjectivity on the pre-consolidation pressure determination, a sensitivity study was conducted. Data plots of all three methods were chosen from the project data pool. For each method, two representative plots were chosen. One of the two was considered to be very straightforward and simple to use for the given method and the other was considered less simple and somewhat ambiguous for the given method. All six plots were chosen independently, based solely on the criteria mentioned above. These plots were then given to undergraduate civil engineering students enrolled in a soil mechanics course. At the time the study was conducted, the students were near completion of the course. Before determining the pre-consolidation stresses, the students were given a reminder of how to perform each of the three methods. Each student determined the pre-consolidation stress for all six plots and sixteen students total participated in the study. The results in the form of standard deviation are shown in FIG. 1:

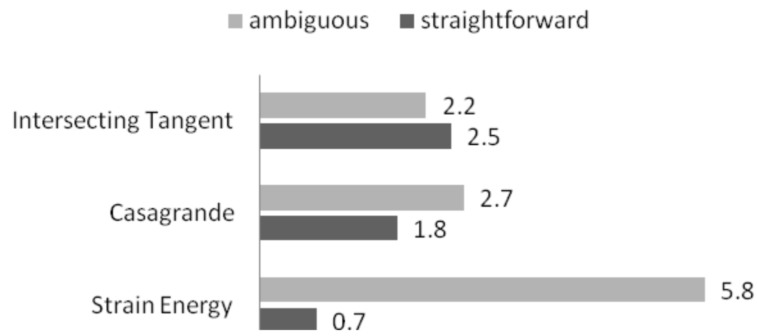

FIG. 1. Results of sensitivity study.

As can be seen in the results, the strain energy method has the highest sensitivity to subjectivity in the ambiguous case but the lowest in the straightforward case. This is consistent with the experiences of the data interpreters for the project. Interestingly, the intersecting tangent method is not much less sensitive than the Casagrande method. This is somewhat surprising because the level of complexity of the Casagrande method is so much higher than that of the intersecting tangent method. Perhaps that very level of complexity leaves less room for variability.

Results

The sample pool used for this study consisted of 26 specimens. The soil for each test was classified using Casagrande's Plasticity Chart and the Atterberg limits (ASTM D2487). Most of the soils tested classified as low plasticity clay (CL) with a couple classified as high plasticity clay (CH).

The standard one-dimensional consolidation (ASTM D2435), also known as the odometer test, was performed on each specimen to determine its pre-consolidation pressure. This method allows strain and drainage only in the vertical direction, applying incremental loads (pressures) ranging from approximately 6.8 Pa (1.0 psi) to approximately 772.2 Pa (112.0 psi). The three methods (Casagrande, intersecting tangents and strain-energy) were used to obtain the pre-consolidation pressures of each specimen. Depth versus effective pre-consolidation pressures for each method, are shown in Figures 2-5.

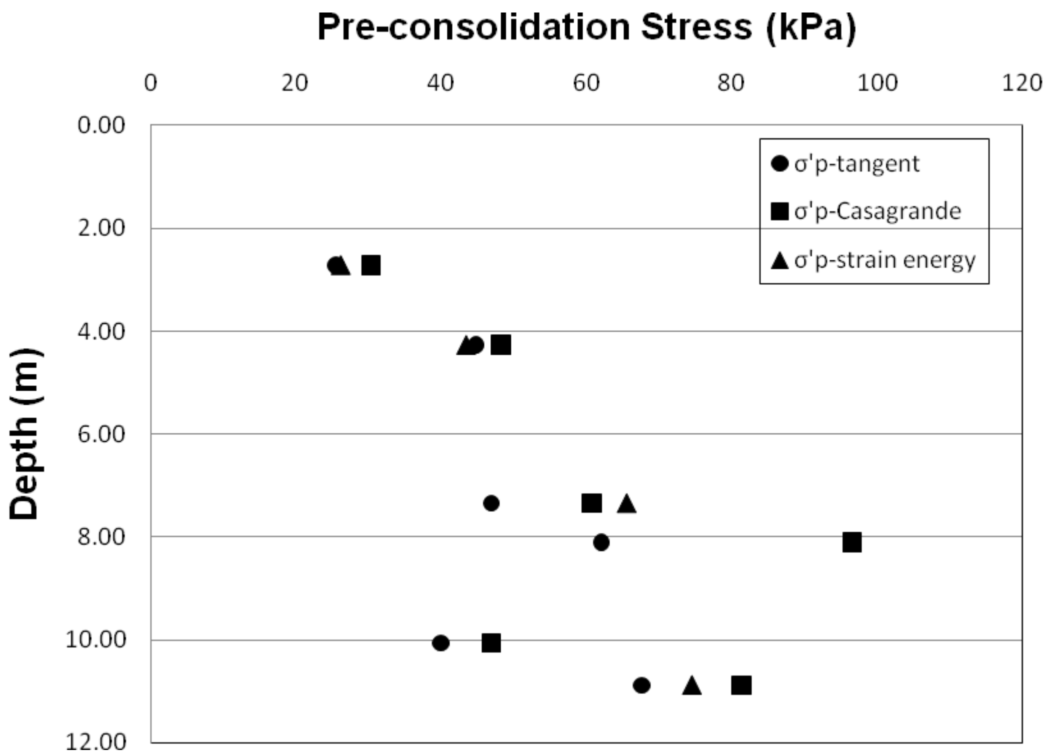

FIG. 2. Pre-consolidation pressure profile for borehole B1.

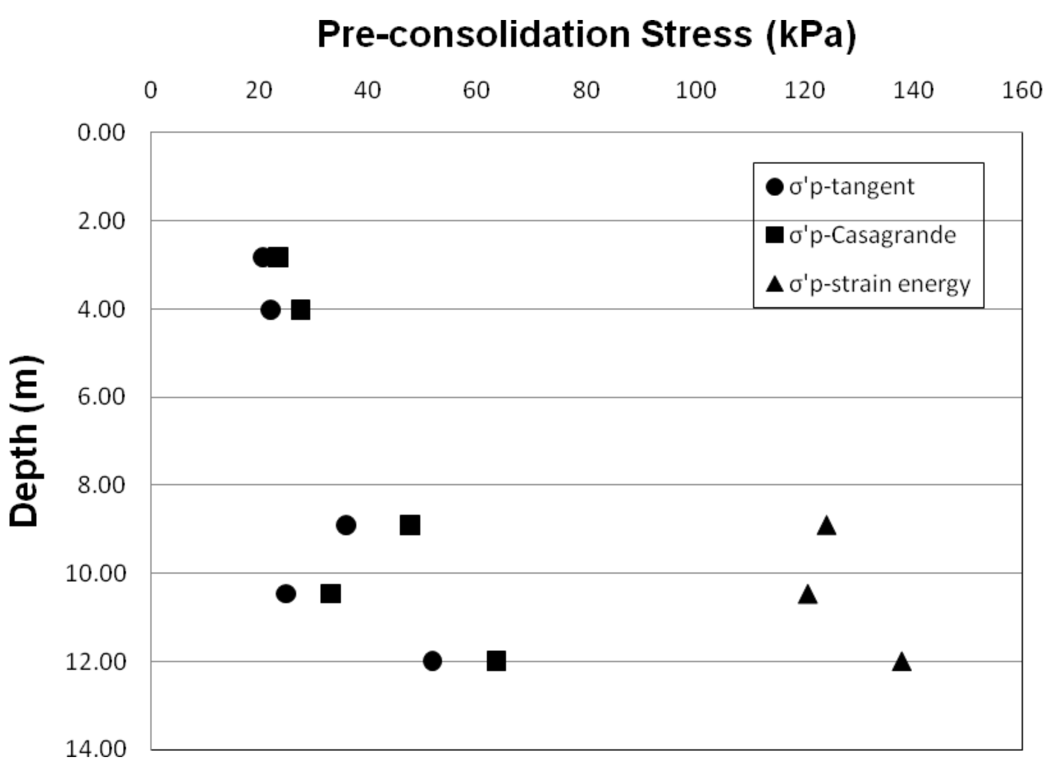

FIG. 3. Pre-consolidation pressure as profile for borehole B2.

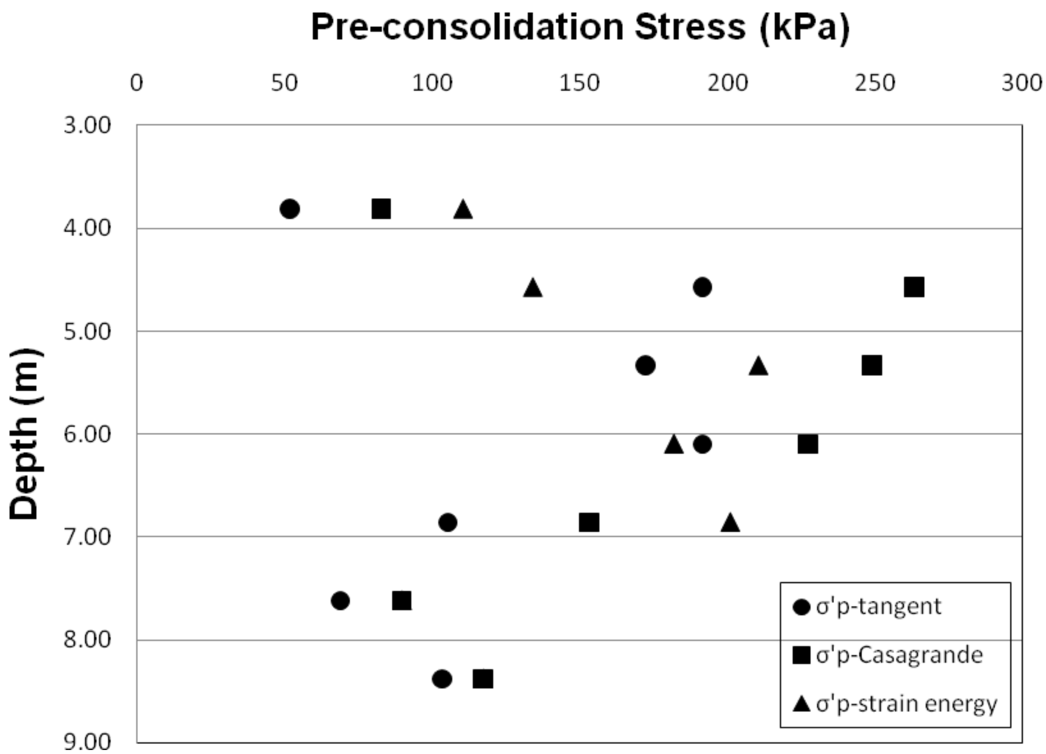

FIG. 4. Pre-consolidation pressure profile for borehole B3.

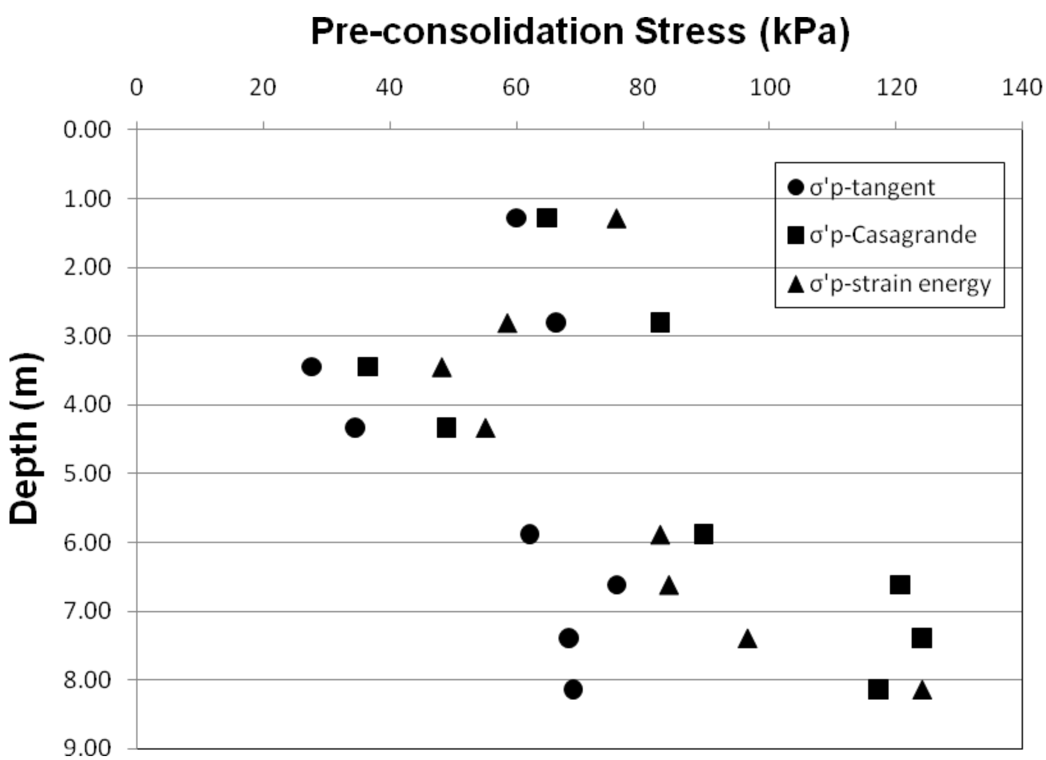

FIG. 5. Pre-consolidation pressure profile for borehole B4.

As evident from Figures 2-5, the pre-consolidation pressures tend to increase with depth but not in all the cases. This is likely because of changes in the soil strata. The intersecting tangent method yielded the lowest pre-consolidation pressures in most cases. The Casagrande method yielded the highest pre-consolidation pressure. The strain-energy method appeared to yield pre-consolidation pressures values in between the values of the other two methods. However, borehole B2 was the exception to the general trends described above. The geology and plastic indices of the borehole B2 sample was very similar to that of borehole B1 and came from the same site as borehole B1. All samples were tested and analyzed identically. This disparity from the general trend remains unknown.

OTHER CONTRIBUTING FACTORS

It is important to keep in mind that the pre-consolidation stress obtained from the consolidation test only represents the conditions at the point where the sample was obtained. If the sample had been taken at a different elevation, the pre-consolidation stress would change accordingly.

There are several factors that may affect the determination of the pre-consolidation stress. A large factor affecting all laboratory testing in soils is sample disturbance. While soil disturbance is still not understood completely, it lowers the magnitude of pre-consolidation pressure and the volume of voids for any given value of effective pressure. Terzaghi (1941) concluded that every clay passes from a solid to a partially lubricated state during sampling operations. This leads to a loss of information regarding the physical properties of clays in the solid state overburden pressure. In other words, as the disturbance of the sample tested increases, the shape of the consolidation curve deteriorates. The "break" in curve becomes less sharp with increasing disturbance, therefore, making it more difficult to determine the pre-consolidation pressure using the current methods. For example, it has been demonstrated that with sensitive clays increasing sample disturbance lowers the value of the pre-consolidation stress. At the same time the void ratio is decreased (or strain increased) for any given value of overburden pressure. As a consequence, the compressibility at stresses less than the pre-consolidation stress are increased, and at stresses greater than the pre-consolidation stress the compressibility is decreased (Holtz, 1981).

CONCLUSIONS

This study indicates that the intersecting tangent method will generally yield the most conservative pre-consolidation pressure. The Casagrande method will typically yield the least conservative pre-consolidation pressure of the three methods. The strain-energy method usually yields a pre-consolidation pressure value between those of the other two methods. However, the use of the strain-energy method is not recommended if the data points are difficult to interpret.

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