Laboratory Evaluation of the Briaud Compaction Device

David M. Weidinger[1] and Louis Ge[2]

Abstract: Soil compaction quality control plays an important role in earthwork construction. Compacted dry density is only loosely related to the actual deformation of the compacted soil. Rather than using dry density as the controlling factor for compacted fills, it would be better to measure properties more closely related to soil compressibility. The Briaud compaction device (BCD) is a simple, small-strain, nondestructive testing apparatus that can be used to evaluate the modulus of compacted soils. The use of the BCD as a field testing device for compacted soil quality control may be more beneficial than the current practice of measuring in situ dry density. In this study, the laboratory procedures of the BCD were evaluated for compacted silt. The modulus determined by the BCD was compared to the dynamic elastic moduli (Young's and shear moduli) determined from ultrasonic pulse velocity testing on the same compacted silt samples. The BCD modulus correlated well with the ultrasonic pulse velocity results with R2 value of 0.8 or better. Finally, a repeatability and reproducibility study conducted on the BCD showed a variation of 4% from the mean when only the soil properties were altered.

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Introduction

Current practice of compaction control has been in place for decades and consists of determining a maximum dry density in the laboratory then specifying a percentage of that maximum to be achieved in the field. However, dry density does not provide a direct relation to the deformation of the compacted soil due to traffic load. Modulus was then considered to be a better parameter for quality control/quality assurance (QA/QC) of compacted soil.

There are several field testing devices available for field modulus evaluation (Lenke et al. 2003; Li 2004; Alshibli et al. 2005; Chen et al. 2005; Ampadu and Arthur 2006; Briaud et al. 2006; Lin et al. 2006). Some are cumbersome, require specialized training, and only loosely correlate values obtained from the device with actual modulus values that can be determined in the laboratory. Unfortunately, there is no existing comprehensive and convenient test or method for determining modulus based compaction specifications in the laboratory that can be monitored easily in the field.

The Briaud compaction device (BCD) is a simple, small-strain, nondestructive testing apparatus that can be used to evaluate the modulus of compacted soils. The BCD works by applying a small repeatable load to a thin plate in contact with the compacted soil of interest. The resulting deflections of the thin plate are measured with an assortment of radial and axial strain gauges mounted on the thin plate. The software within the device uses correlations determined from field and laboratory tests to calculate a low strain modulus (strain level at 10^{-3}, stress level at 50 kPa, and time of loading of a few seconds), referred to as the BCD modulus.

Ultrasonic pulse velocity testing is a pulse transmission test that sends waves that range in frequencies from 20 kHz to 1 GHz through a soil specimen to produce strains on the order of 10^{-5} (Leong et al. 2004). The test is nondestructive and can be used to determine the velocities of the longitudinal and shear waves that propagate through the soil specimen. The dynamic elastic constants can be determined using the wave velocities based on the theory of elasticity for homogenous and isotropic solids. The strain levels associated with the BCD and the ultrasonic pulse velocity device differ by as much as two orders of magnitude. Because of the smaller strain levels, moduli determined from the ultrasonic pulse velocity device can be expected to be larger than those of the BCD but should still correlate reasonably well. This study attempts to correlate the BCD modulus to the dynamic moduli obtained from ultrasonic pulse velocity testing and to evaluate the repeatability of the BCD.

Experimental Setup

Material

The material used in this study is a modified loessial low plastic silt that comes from the Mississippi River Valley near Collinsville, Illinois. The silt has a liquid limit of about 30, a plastic limit of about 24, and natural clay content of about 17.0%. The material is classified by the Unified Soil Classification System as an ML soil (Izadi 2006). Previous studies with the BCD have been focused primarily on clays and some sands so an investigation on a low plastic silt should be beneficial to the development of the device.

Three standard proctor compaction tests were conducted per ASTM D 698. Each test used six points to establish the second-order polynomial best fit curve. The points ranged from 10% to

[1]Staff Geotechnical Engineer, Vector Engineering Inc., Grass Valley, CA 95945; formerly, Graduate Student, Dept. of Civil, Architectural, and Environmental Engineering, Missouri Univ. of Science and Technology, 1401 North Pine St., Rolla, MO 65409. E-mail: weidinger@vectoreng.com

[2]Assistant Professor, Dept. of Civil, Architectural, and Environmental Engineering, Missouri Univ. of Science and Technology, 1401 North Pine St., Rolla, MO 65409 (corresponding author). E-mail: geyun@mst.edu

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20% at increments of 2% in moisture content. Two modified proctor compaction tests were conducted to establish the modified proctor compaction curve per ASTM D 1557. Again, six points were investigated and they ranged from 8–18% at increments of 2% in moisture content. The BCD test uses a 152.4-mm (6-in.) proctor mold for testing. All compaction efforts were made with a mechanical automatic proctor hammer to a tightly controlled compaction energy. The automatic hammer was recalibrated between each test. The optimum moisture content (OMC) and maximum dry density for the standard proctor compaction test is 14.5% and 16.8 kN/m^3, respectively; the OMC and maximum dry density for the modified proctor compaction test is 12.0% and 17.7 kN/m^3, respectively.

Specimen Preparation

The soil was first mechanically pulverized then passed through a #40 sieve (425 mm). The soil was moistened to a predetermined moisture content then allowed to cure for 24 h. The soil was then compacted into a 152.4 mm (6 in.) split proctor mold, whose inside was lubricated with silicone spray to aid in specimen extrusion. Samples were prepared to match dry densities and moisture contents previously determined from the proctor compaction tests. After soil compaction, the top of the samples were finished smooth for BCD testing.

Briaud Compaction Device Testing

The purpose of the BCD laboratory test is to establish a modulus versus moisture content relationship, similar to the dry density versus moisture content relationship established from proctor compaction tests. The BCD has two modes of operation that account for the boundary effects of the proctor mold that would not occur in the field (Li 2004). The laboratory testing mode was selected in this study. To get a good average of the BCD modulus, four measurements were taken rotating the BCD 90° between each test then averaged to get the BCD modulus (Li 2004).

Ultrasonic Pulse Velocity Testing

Ultrasonic pulse velocity tests were conducted on the compacted soil samples in an attempt to correlate BCD modulus with dynamic soil moduli.

After the compacted soil was tested with the BCD, it was extruded, sealed, and placed in a moist cure room until ultrasonic pulse velocity testing could be conducted. All pulse velocity measurements determined in this study came from a GCTS ULT-100 ultrasonic velocity test system. The ultrasonic testing setup used could not accommodate 152.4-mm diameter samples, so a sample trimmer was used to carefully trim the samples to a diameter of 70 mm (2.8 in.). A normal load of 50.0 ± 5.0 N (11.3 ± 1.2 lbf) with no confinement pressure was applied. Initial tests revealed at full specimen height of 114 mm (4.5 in.) that the attenuation through the silt samples was too great and no conclusive arrival times could be retrieved. Therefore, the samples were sliced into thirds (approximately 40 mm) and finished smooth. Tests conducted on the shorter samples resulted in clean data with a high amplitude of frequencies matching the predetermined original wave frequencies indicating a good test (Weidinger et al. "Ultrasonic pulse velocity testing on compacted silt." *Can. Geotech. J.*, 2009).

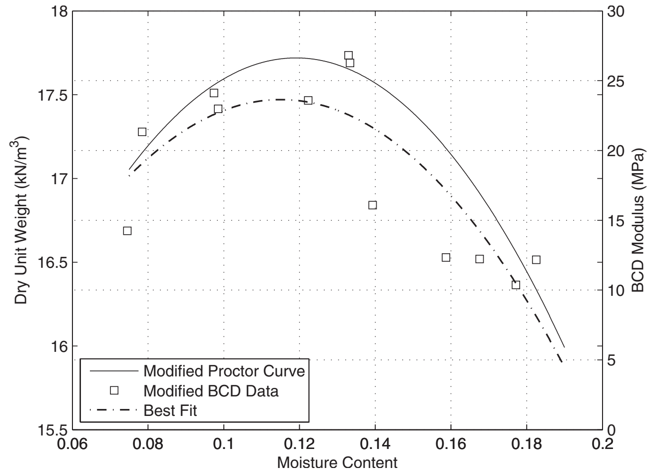

Fig. 1. Modified BCD modulus versus moisture content in comparison with the modified proctor compaction curve

Results and Discussions

Briaud Compaction Device Testing

The overlapping curves of BCD modulus and dry unit weight versus moisture content are presented in Figs. 1 and 2 for modified and standard proctor compactions, respectively. For the modified proctor tests, the BCD modulus follows a similar trend as the compaction curve. The maximum BCD modulus for the modified tests was found to be 23.7 MPa and a corresponding moisture content of 11.5%. The modified proctor OMC is 12.0% for this soil, which is very close to the BCD modulus OMC. Results from this study, as well as results from other works (Lenke et al. 2003; Briaud et al. 2006), verify that the modulus follows a similar trend to that of the compaction curve with an OMC occurring at or around the OMC for dry unit weight.

However, BCD results from the standard proctor tests yields a different curve, in both shape and location. The regression fit does not make a symmetric polynomial curve like the compaction curve does. Instead, the curve simply decreases with increasing moisture content and produces a slight peak around 12.0% moisture content. It appears that if more tests were conducted at lower

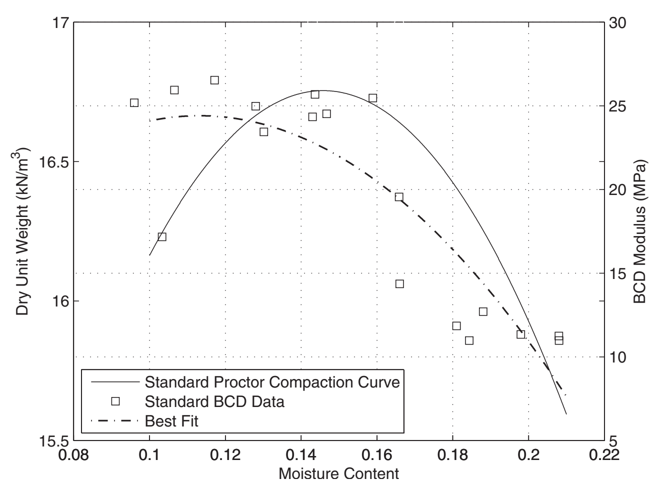

Fig. 2. Standard BCD modulus versus moisture content in comparison with the standard proctor compaction curve

moisture contents, a full curve might be established. The peak at 12.0% moisture content is drier than the optimum standard proctor moisture content of 14.5%, which is somewhat expected since soil suction and interparticle friction tend to increase modulus at lower moisture contents. On the other hand, the modified compaction effort may have enough energy to overcome some of these effects. In both the standard and modified tests the BCD modulus dropped quickly as the moisture content increased from the OMC, typically reducing by one-half with a 5% increase in moisture content.

During the BCD testing, several factors were identified that can significantly influence the test results. The BCD applies the load by the operator leaning on the unit. If the operator does not apply the load vertically then the soil is loaded nonuniformly resulting in a lower modulus reading than expected. Currently, the BCD does not have a mechanism to determine if the device is plumb. The addition of a bubble level or similar type of mechanism might help eliminate this problem. Second, the diameter of the BCD loading plate is 150 mm and the standardized 6 in. proctor mold diameter is 154.2 mm, allowing a little over 2 mm of spacing between the load plate and the proctor mold. The small 2-mm margin requires care to ensure the BCD is centered as closely as possible. Inattention to the BCD positioning can result in the load plate being too near or touching the mold. This can greatly alter the test result, typically by increasing the recorded BCD modulus. The surface of the proctor compacted specimen must be finished flat and smooth. Undulations in the surface of the compacted soil puck will cause increased load plate deformations, resulting in a lower BCD reading.

Gauge R and R Analysis

The repeatability of the BCD was investigated using the BCD data collected from the five proctor curves (three standard and two modified). In this case, repeatability was examined by conducting the gauge repeatability and reproducibility (gauge R and R) analysis. Typical gauge R and R studies determine the effect of several operators (field/lab technicians) conducting multiple iterations of a test on several different specimen using one device. In that framework, variation in the results is a function of the operator, the device (the BCD), and the soil. For this study, operator variance was eliminated by conducting all tests with one operator. From the repeatability analysis, the standard deviation of the BCD modulus was found to be 0.85 MPa. The average BCD modulus for the soil used was 20 MPa, which means that repeated BCD measurements should be within a variation of 4% from the mean. The results were found closer to the study by Briaud et al. (2006) where they conducted several repetitions of the test at one location and found the coefficient of variation to be below 4%.

Pulse Velocity

As mentioned earlier, the original sample height used for the BCD had to be sectioned into a top, middle, and bottom section with heights ranging from 25–40 mm. Li (2004) reported that the influence depth of the BCD modulus decreases from 311 to 121 mm as the modulus increases from 3 to 300 MPa under large loads. Numerical simulations show that the influence depth of the BCD under the actual testing loads (approximately 220 N) is much smaller. It is reasonably assumed that pulse velocity tests on the top sections of the compacted soil samples correspond to the same material properties tested by the BCD. Therefore, only the pulse velocity data from the top soil samples were compared to the BCD modulus.

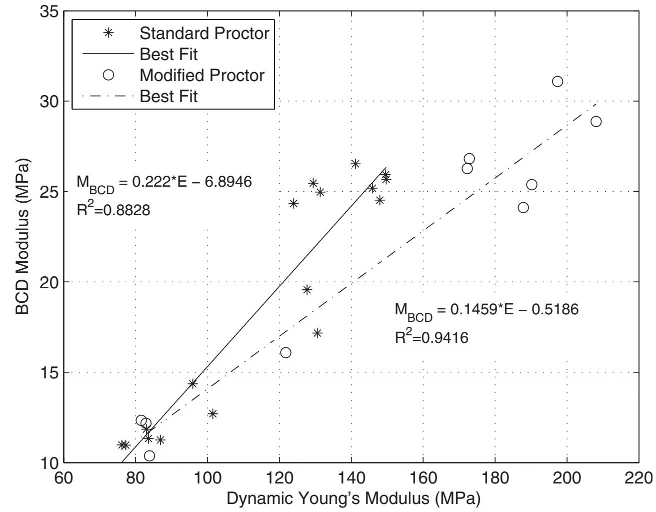

Fig. 3. BCD modulus versus dynamic Young's modulus

The BCD moduli versus the corresponding dynamic Young's moduli found from pulse velocity tests are plotted in Fig. 3. The data have been separated according to compaction effort (i.e., standard proctor and modified proctor). Both sets of data produce well fitted trends with the standard proctor data having a steeper slope. Similarly, the BCD Moduli versus the corresponding dynamic shear Moduli are plotted for both standard and modified energy in Fig. 4. Again, a greater slope for the standard proctor trend line was observed. Though the BCD modulus is not the same as the dynamic shear or Young's moduli determined for each specimen, the strong correlations to other moduli suggests that the BCD is indeed reporting a form of modulus that could be correlated with other moduli determining tests with significant accuracy.

Comparison of the BCD moduli to the dynamic elastic moduli determined from the ultrasonic pulse velocity test shows a high correlation. Other studies have reported that the BCD test produces a modulus that correlates well with various moduli tests

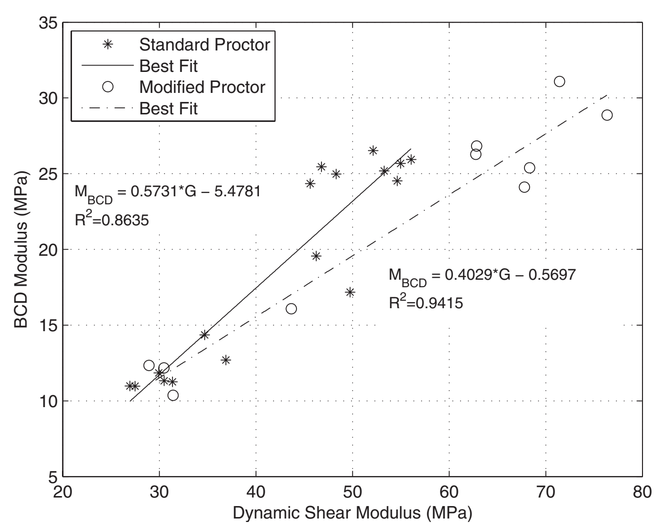

Fig. 4. BCD modulus versus dynamic shear modulus

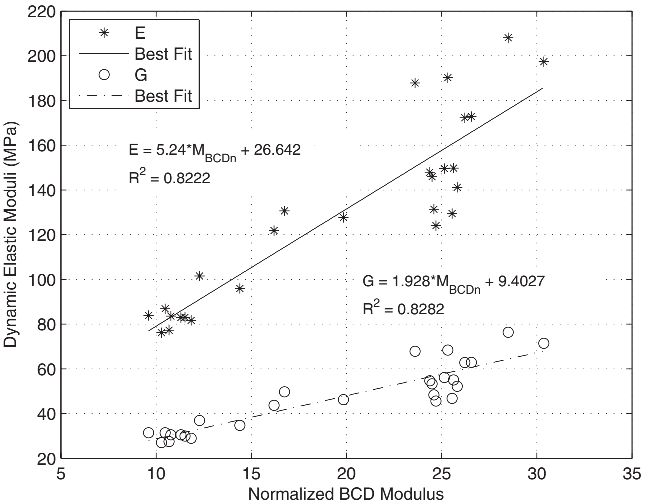

Fig. 5. Dynamic elastic moduli (E and G) versus normalized BCD modulus

such as the plate load and the resilient modulus tests (Li 2004; Rhee 2004). Therefore, it is not surprising that the BCD correlates well with the dynamic elastic moduli. The slope of the linear trends describing the relationship between the BCD moduli and dynamic elastic moduli was steeper for the standard compaction energy when compared to the modified compaction energy. Varying the compaction energy alters the soil fabric, meaning the two samples compacted to the same dry density with different energies will produce soil with different particle arrangements. To account for the different compaction energies used, the BCD moduli was normalized by multiplying the moduli by the relative compaction. Relative compaction refers to the dry density obtained for each test divided by the maximum dry density corresponding to the compaction effort ($16.8\ \text{kN/m}^3$ for the standard proctor and $17.7\ \text{kN/m}^3$ for the modified proctor). The dynamic elastic moduli (G and E) did not require normalization because the density of the soil is already accounted for in the equations that derive the moduli from the wave velocities. The BCD moduli, however, does not account for soil density. Fig. 5 shows the dynamic Young's and shear moduli versus the normalized BCD moduli. Good correlation occurs for the data with R^2 value above 0.82.

Conclusions

The BCD is a simple nondestructive testing tool that can determine a modulus for soil compaction control. Other moduli tests can be used for determining a field modulus but, due to their size and boundary effects, they cannot easily be conducted in a laboratory setting. This drawback limits their usefulness. Without a laboratory value to compare to, only correlations to other lab tests can be used to specify a target field modulus. Correlations are typically soil specific. With the BCD, the operator can conduct a laboratory test to produce a BCD moduli compaction curve (similar to the proctor compaction curve) then compare BCD moduli values obtained from the field directly to BCD modulus values from the lab test. This is an attractive alternative to soil compaction control using the dry density method because first, the BCD directly measures a modulus to determine the compaction state of soils, and second, the BCD can easily be used in the lab as well as the field so one tool will do it all.

Laboratory testing with the BCD is based on the proctor compaction test standards. Because the BCD is based on the proctor compaction test, no additional lab equipment is required. Conducting BCD tests on the proctor compacted soil is simple and does not require a great deal of extra time on the technician's part, allowing two important soil trends to be established: the dry density versus moisture content curve and the BCD modulus versus moisture content curve. When used in parallel, field compaction specifications could be established based on both dry density and modulus, ultimately producing a compacted soil layer that would be both uniformly dense and strong.

In addition, this study indicates that the BCD modulus can be compared to other moduli determining tests such as the ultrasonic pulse velocity test. Trends such as the ones determined from Figs. 3–5 could be used to determine the in situ dynamic moduli of a soil by simply conducting a BCD test in the field. This could prove useful in seismic and machine foundation design on existing compacted soil layers.

However, it should be noted that due to the limitation of the BCD's influence depth, it would be difficult to effectively assess the soil modulus beyond several inches below the ground surface. In this regard, the value of the BCD might be somewhat limited when compared to other QA/QC methods which assess soil characteristics to greater depths.

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