Characterizing bulk modulus of fine-grained subgrade soils under large capacity construction equipment

Joseph ANOCHIE-BOATENG[1]
CSIR Built Environment, Pretoria, South Africa

Abstract. This paper focuses on characterizing the volumetric stiffness behavior of fine-grained subgrade soil at three different moisture states using a newly proposed hydrostatic compression test procedure. The deformation properties obtained from a laboratory testing program were used to determine bulk modulus at varying hydrostatic stress states, and moisture states chosen at optimum moisture content, 3% below and 3% above the optimum. The test results are analyzed, and used to develop regression correlation models for the soil sample tested. These models can be used for evaluating the impact of moisture on bulk modulus of fine-grained soils with similar characteristics for their sustainable use in foundation applications under off-road construction and compaction equipment.

Keywords. Bulk modulus, hydrostatic stress, subgrade soils, construction equipment,

Introduction

The routine operations of large capacity off-road construction equipment on fine-grained cohesive soils have become a concern to the construction and equipment manufacturing sectors. A major problem is the mobility (trafficability) of large haul trucks and shovels during field operations on these soils. Cohesive fine-grained and cohesionless granular soils constitute the foundation of highway and airport pavements as well as railroad track. These materials would exhibit different load bearing capacities at different stress and moisture states under construction equipment. To understand behaviour of these foundation materials under large capacity construction and compaction equipment it is important to properly address the true volumetric deformation characteristics under all-around uniform normal stress conditions.

Bulk modulus is an important material property that describes the resistance to volume change when an element of soil is subjected to all-around hydrostatic loading [1]. In this paper, bulk modulus is determined in the laboratory for a selected fine-grained cohesive soil using a newly developed hydrostatic compression test procedure [2]. The test procedure considers field loading characteristics of off-road construction haul trucks and shovels to determine bulk modulus at varying hydrostatic stress states, and moisture states chosen at the optimum moisture content, 3% below and 3% above

[1] Corresponding Author. Senior Researcher, CSIR Built Environment, Transport Infrastructure Engineering, Bldg 2C, P O Box 395, Pretoria, 0001, South Africa; E-mail: JAnochieboateng@csir.co.za

the optimum. The bulk modulus together with shear modulus will be used to obtain the elastic modulus and Poisson's ratio of the soil sample.

1. Laboratory Testing Program

1.1. Properties of Soil Sample

The fine-grained cohesive soil investigated in this paper was obtained from Caterpillar Inc. field demonstration test sections in Illinois, and was shipped to the University of Illinois Advanced Transportation Research and Engineering Laboratory (ATREL) for testing. The sample was a clayey soil, a "CL" according to the United States unified soil classification system or an "A-6" according to the American Association of State Highway and Transportation Officials (AASHTO) classification, with a liquid limit (LL) of 27.2, a plasticity index (PI) of 13.1, and composition of 0.3% gravel, 29.5% sand, 40.9% silt, and 29.3% clay. Accordingly, the soil sample was designated herein as SA-6. From the standard Proctor [3] test procedure, the maximum dry density obtained was 18.4 kN/m^3 at an optimum water content (w_{opt}) of 14.3 %. The dry densities at the moisture states of 3% below and 3% above the optimum were 18.0 kN/m^3, and 17.6 kN/m^3, respectively

1.2. Laboratory Testing Procedure

The loading characteristics of off-road large capacity construction and compaction equipment dictate field loading stress states and therefore directly influence the volumetric deformation and stiffness behavior of soils in the field. For instance, Joseph [4] noted from field studies that a Caterpillar 797B off-road haul truck could produce vertical stresses of about 800 kPa with confining stresses ranging between 250 and 300 kPa. He also observed that the P&H 4100 type BOSS shovels generated a static vertical loading of up to 220 kPa, and could induce a ground confinement of about 70 kPa [4]. It is expected that the soil would undergo anisotropic loading conditions. However, under the laboratory triaxial testing conditions ($\sigma_2 = \sigma_3$), thus, an isotropic conditions was used in this study to simulated the volumetric hardening of the SA-6 soil.

An innovative advanced triaxial testing device, the University of Illinois FastCell (UI-FastCell) integrated with an Universal Testing Machine (UTM) loading device at ATREL could be used to achieve the field loading conditions. The UI-FastCell offers unique capabilities in laboratory material characterization including measurement of on-sample vertical and radial displacements, and a bladder type horizontal confinement chamber with a built-in membrane which can be inflated to apply hydrostatic stresses to simulate high field loading conditions on granular and bituminous materials in the laboratory [5]. Figure 1 shows the UI-FastCell test setup.

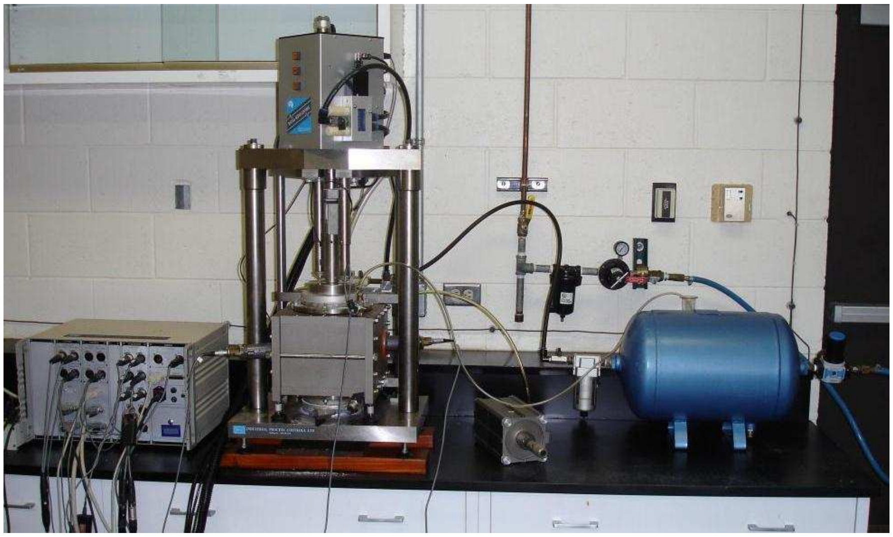

Figure 1. UI-FastCell test setup.

1.3. Hydrostatic Test Procedure

The UI-FastCell was used for applying hydrostatic stresses on the fine-grained soil specimens. The hydrostatic compression test was conducted on 150 mm diameter by 150 mm high pneumatic vibratory compacted specimens. During testing, compacted soil specimens were subjected to a sequence of different applied hydrostatic (isotropic) compression stresses of 20.7, 41.4, 69, and 138 kPa under drained conditions, with volumetric change measurements. Specimens were loaded from zero stress conditions to these individual hydrostatic stresses, unloaded to zero, and then, reloaded to the next stress state until the maximum hydrostatic stress of 276 kPa was reached (i.e., 0 → 20.7 kPa → 0 → 41.4 kPa → 0 → 69 kPa → 0 →138 kPa → 0).

A pulsed wave shape with 60-second loading and 60-second unloading was applied on the test specimens at each stress state. The loading rate was maintained in such a way that no pore pressure was induced. The axial static loading was controlled by the vertical load cell, and the radial loading was measured by a pressure transducer. To achieve isotropic condition, the UTM software was adjusted to ensure that equal radial and vertical loads were applied to the sample. Both axial and radial deformations were measured by two symmetrical linear variable displacement transducers (LVDTs) for each load cycle and the corresponding axial and radial strains (ε_1 and ε_3) are computed for the test specimens. Two replicate tests were performed for the soil sample at three moisture states of 11.3%, 14.3% and 17.3%. Overall, 12 tests were conducted on the soil sample at the three moisture conditions.

2. Analyses of Test Results

The applied hydrostatic stresses and measured volumetric strains obtained from hydrostatic compression tests are used to calculate bulk modulus. A plot of the applied isotropic compression stress against volumetric strain gives a nonlinear curve for soils [6-8]. Vesic and Clough [7] suggested that the soil's elastic properties could conveniently be obtained from the nonlinear curve by straight line approximations that linearly relate increments of both the isotropic stress and volumetric strains. In this study, the straight line approximation concept was used for analyzing the test results of the samples. The bulk moduli K of the soil sample was calculated from the ratio of the incremental hydrostatic stress $\Delta\sigma$ to the incremental volumetric strain $\Delta\varepsilon_v$. Eq. (1) was used to define the bulk modulus of the soil sample tested:

$$K = \frac{\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3}{\Delta\varepsilon_v} = \frac{\Delta\sigma}{\Delta\varepsilon_v} \tag{1}$$

where the volumetric strain ε_v is computed from the axial strain ε_1 and radial strain ε_3 as $\varepsilon_v = \varepsilon_1 + 2\varepsilon_3$; for triaxial compression tests, hydrostatic stress is given by $\sigma = \sigma_1 = \sigma_2 = \sigma_3$.

A total of about 270 stress-strain data sets for each test were analyzed for the bulk modulus of the soil sample at one moisture state. Each data set represents an average value from the two replicate specimens. Figure 2 shows a plot of the applied hydrostatic stress against the total volumetric strain for SA-6 soil sample at the three moisture states. It can be demonstrated from figure 2 that the behaviour of the SA-6 soil could be linear (i.e., constant K) up to a hydrostatic stress of about 80 kPa, and therefore, complying with Eq. (1). However, it can be seen from the figure that above certain threshold hydrostatic stress states, the bulk modulus–hydrostatic stress relationship presented in Eq. (1) for soils may not necessarily be applicable under certain conditions. The straight line approximation was used to obtain the incremental hydrostatic stresses and corresponding volumetric strains. The bulk modulus was then computed at each hydrostatic loading stress using Eq. (1).

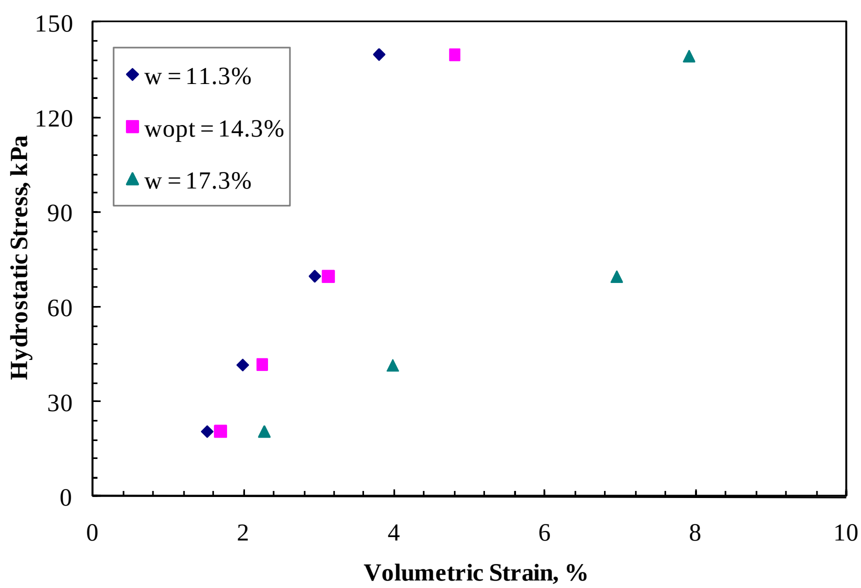

Figure 2. Variation of stress with strain.

Table 1 lists test results of the SA-6 soil at the three moisture states. As expected, the soil sample at dry of optimum gave the highest bulk modulus values whereas the lowest bulk modulus values were obtained at wet of optimum. The average bulk modulus value increases by 1.1 MPa from optimum (dry density of 18.3 kN/m^3) to dry of optimum (dry density of 18.0 kN/m^3), and decreases by an average of 1.2 MPa from optimum to wet of optimum (dry density of 17.6 kN/m^3). Thus, a change in water content of 3% below the optimum resulted in about 38% increase in the bulk modulus of the soil sample, whereas a change in water content of 3% above the optimum resulted in about 42% decrease in the modulus values. The high lubrication of soil particles at wet of optimum water content weakens the soil sample. Therefore, the modulus of the sample becomes low at wet of optimum when compared to dry of optimum, or the soil becomes less sensitive at dry of optimum.

Figure 3 shows the correlations between bulk modulus as linear functions of hydrostatic stress for the soil sample at the three moisture states. The significantly high coefficients of correlation values indicate that the straight line incremental approximation concept (Eq. 1) used for the analyses performed well for the SA-6 sample at all three moisture states.

Table 1. Test results for SA-6 soil at three moisture states.

$\Delta\sigma$ (kPa)	w =11.3%		w_{opt} = 14.3%		w = 17.3%	
	$\Delta\varepsilon_v$ (%)	*K* (MPa)	$\Delta\varepsilon_v$ (%)	*K* (MPa)	$\Delta\varepsilon_v$ (%)	*K* (MPa)
20.7 – 41.4 (20.7)	0.68	3.15	0.88	2.43	1.35	1.58
41.4 – 69.0 (27.6)	0.62	4.45	0.82	3.36	1.65	1.67
69.0 – 138.0 (69.0)	1.00	6.90	1.60	4.31	2.60	2.65

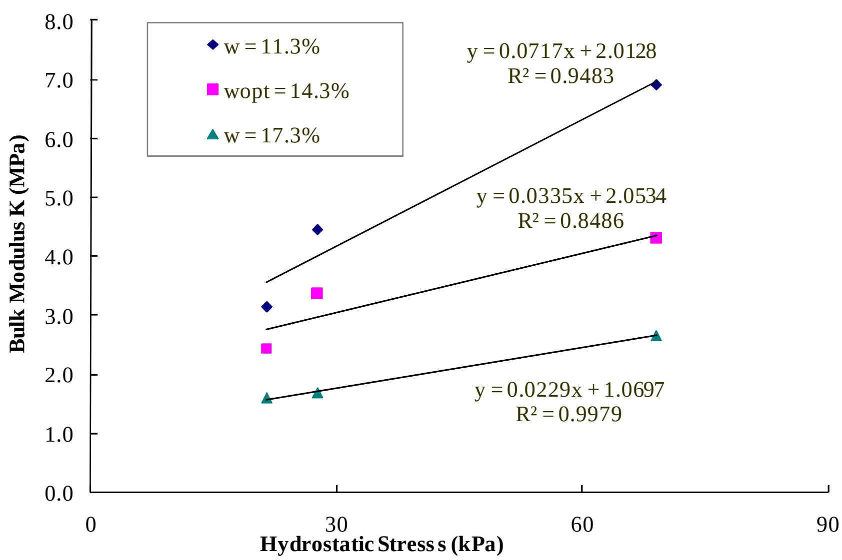

Figure 3. Correlations between bulk modulus and hydrostatic stress at three moisture states.

3. Summary and Conclusions

Hydrostatic triaxial compression tests were performed on a fine-grained cohesive soil sample in the laboratory using a newly developed hydrostatic loading test procedure. The laboratory tests were performed to determine bulk modulus at three moisture states of 11.3%, 14.3% and 17.3%, representing dry of optimum, optimum and wet of optimum, at dry densities of 18.0 kN/m^3, 18.3 kN/m^3 and 17.7 kN/m^3, respectively. The test procedure applies low to high hydrostatic stress levels on the specimens to simulate the laboratory loading behavior of fine-grained soils under construction and compaction equipment.

Moisture content affected the bulk modulus properties of the soil sample as it was evident that at the high moisture state, the sample exhibited low bulk modulus when compared to low moisture state, at which the sample had high bulk modulus. The test results provide a database of bulk modulus properties for the soil at the three moisture states.

Based on the test results, bulk modulus correlations in the form of linear functions of the applied hydrostatic stress were established for the soil sample at the different moisture states. The anticipated use of the regression correlation equations would provide essential guidelines for predicting volumetric deformation behavior of the fine-grained subgrade soil in the field. In addition, the bulk modulus data obtained through this study will be useful for engineers and construction equipment manufacturers to estimate volumetric loading characteristics and stiffness behaviour under construction haul trucks and shovels in the field for the soil tested, and other fine-grained cohesive soils with similar characteristics.

Acknowledgements

The author would like to acknowledge Professor Erol Tutumluer of University of Illinois at Urbana-Champaign, and Dr. Liqun Chi of Caterpillar, Inc. of Peoria, Illinois for their support in this study.

References

[1] S.L. Kramer, *Geotechnical Earthquake Engineering*, Prentice Hall, New Jersey, 1996.

[2] J.K. Anochie-Boateng. *Advanced testing and characterization of transportation soils and bituminous sands*, PhD Thesis, University of Illinois at Urbana-Champaign, Urbana, 2007.

[3] AASHTO T 99-01. *Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop*, American Association of State and Highway Transportation Officials, Washington DC, 2004.

[4] T.G. Joseph, Physical, static and inferred dynamic loaded properties of oil sand. *Final Progress Report*, Phases I, II, & III, submitted to Caterpillar, Inc., Peoria, 2005.

[5] E. Tutumluer, and U. Seyhan, Laboratory determination of anisotropic aggregate resilient moduli using a new innovative test device, *Journal of Transportation Research Board* **1687**, (1999). 13 – 21.

[6] K. Terzaghi, and R. B. Peck, *Soil Mechanics in Engineering Practice*, 2nd ed. Wiley, New York, 1967.

[7] A.B. Vesic, and G.W. Clough, Behavior of granular material under high stresses. *Journal of the Soil Mechanics and Foundation Division* **94** (1968.): 661 – 668.

[8] B.S. Quabin, V.N. Kaliakin, and J.P. Martin, Variable bulk modulus constitutive model for sand, *Journal of Geotechnical and Geoenvironmental Engineering* **2** (2003), 158 – 162.