Consolidation Properties of Barind Soil in HC Stress Path Method

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Abstract

This paper presents the consolidation properties, volume change behaviour and bulk modulus of barind soil using computer controlled triaxial apparatus. The research program was concentrated on the study of hydrostatic triaxial compression (HC) tests on 50 mm diameter and 100 mm high specimens. Hydrostatic stress path tests have been conducted with different consolidating pressure ranging between 50 kPa to 1400 kPa. Three loading-unloading-reloading cycles were carried out for each test at consolidating pressure 400, 800 and 1200 kPa respectively. A consistent set of soil design parameters is obtained by analysis of test results representing bulk modulus and volume change properties as a function of mean stress. An analytical model is presented for the calculation of bulk modulus and volumetric strain for unloading-reloading HC stress path. Verification of the model has been made with the experimental triaxial test results. The predicted result is show to fit accurately the entire stress-strain response of soil to incremental loading hydrostatic compression tests.

Keywords: *Consolidation Properties, Triaxial Test, Stress Path, Volumetric Strain, Bulk Modulus.*

1 Introduction

Considerable areas of land throughout the world are formed of fine-grained compressible soils that are not suitable for engineering structures unless any treatment is done. With the rapid increase of population suitable lands are getting scarce for development activities. In many instances, it is necessary to construct buildings, roads, railways and embankments over weak soils. These problems are often analyzed by finite element method. One of the important input parameter in finite element method is bulk modulus to characterize the behaviour of the soil by non-linear elastic model. It is important that the stress-deformation and volume change characteristics of the soil be represented in the analyses in a reasonable way, when the computed results are to be realistic and meaningful. In general, it is not practical to conduct extensive soil tests to obtain the soil properties required by finite element methods during design phase. Thus, the research works aimed to determine the consolidation characteristics of braind soil in hydrostatic compression (HC) stress path test. In this stress path, a specimen starts from an initial hydrostatic or isotropic state of stress $p_o = \sigma_o$. Then it is subjected to increments of hydrostatic or mean pressure, $p = J_1/3$, where $J_1 = \sigma_1 + \sigma_2 + \sigma_3$. The hydrostatic stress test provides information on the volumetric or bulk behaviour of a material. In this test no shear stresses are induced. The observed test data from this test provide evaluation of the bulk modulus (B) and other information, such as the hardening parameters for various constitutive laws. The hydrostatic compression tests are conducted with various initial stress states defined by initial density (γ_o), and initial void ratio (e_o). Measurements are obtained in terms of stresses (loads) and deformations (strains) as the loading progresses. Finally, an attempt was undertaken to determine the model constants and bulk modulus from test results.

2 Material Properties

In this research work, undisturbed clay of 75 mm tube samples was used for HC stress path test. The basic soil properties were determine following the ASTM Standard (2016). The soil is blackish in color and classified as CH in Unified Classification System (USCS). The soil particle contains about 75 % clay, 19 % silt, 06 % sand and no gravels. The other soil properties are: liquid limit 69%, plastic limit 35% plasticity index 34%, and specific gravity 2.63. From the plasticity chart, as suggested by Head (1980), the soil can be classified as CH i.e. high plasticity clay. The natural moisture content was about 34.2%. The coefficient of permeability of compacted residual soil was found to be approximately 2.462 x 10^{-9} m/sec and it indicate that the permeability of the soil is very low (Terzaghi and Peck, 1948; Whitlow, 1995).

3 Testing Program

The testing program was performed by hydrostatic compression stress path (HC) tests on clay. This stress path is followed using the conventional 50 mm dia and 100 mm high cylindrical triaxial samples. Hydrostatic compression tests were conducted for clay to simulate the bulk modulus properties of the clay. In this program, three tests were done. The schematic representation of the HC stress path on triaxial plane is shown in Fig.1. In this stress path, the testing was done at initial consolidation pressure 50 kPa and then increases stepwise to 1400 kPa. In each test, three unloading-reloading cycles at the stress levels 400 kPa, 800 kPa and 1200 kPa were made in order to determine the bulk volume change behaviour. Here, the state of stresses are referred to the principal axes, and the incremental stress tensor for hydrostatic compression test can be expressed as

$$\Delta\sigma_{ij} = \begin{bmatrix} \Delta\sigma_1 & 0 & 0 \\ 0 & \Delta\sigma_1 & 0 \\ 0 & 0 & \Delta\sigma_1 \end{bmatrix} \tag{1}$$

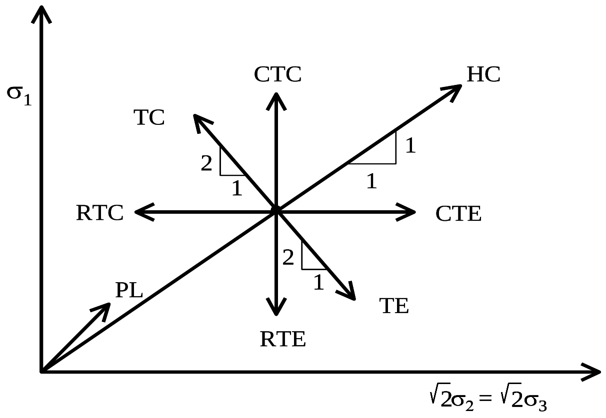

Fig. 1 Schematic representation of the various stress paths on triaxial plane.

4 Testing Procedure

In this investigation, three hydrostatic compression tests were performed on the undisturbed barind soil. The hydrostatic triaxial compression specimens were prepared by trimming from 75 mm tube samples. The specimens were set up between a porous disk at its bottom and a porous disk at the top in the triaxial cell. A rubber membrane was placed over the specimen using a membrane stretcher and O-rings were placed over the membrane on the bottom pedestal and upper cap. Saturation of the test specimens was achieved by continuously increasing the cell pressure and back pressure. The computer controlled triaxial (GDS) system (Fig.2) was adapted to carry out the HC stress path tests that were described by Menzies (1989). A microprocessor collects the data from transducers automatically at prescribed intervals. The data were transmitted by the controlling microprocessor for recording, processing and production of results, which could be displayed on the screen, tabulated or plotted by a plotter.

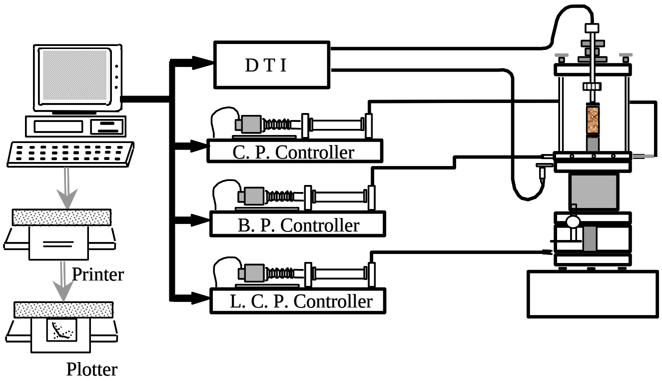

Fig. 2 Schematic diagram of the triaxial testing system for HC stress path.

5 Test Results

The hydrostatic compression path test provides information on the volumetric or bulk behaviour of a soil and in this test no shear stresses are induced. The observed test data provides evaluation of the bulk modulus (B) and other information such as the hardening parameters for various constitutive models. In this stress path, soil samples are subjected to virgin loading, unloading and reloading paths. Three numbers of hydrostatic isotropic compression tests were conducted on clay samples. The mean stress versus volumetric strain plots of sample 1, sample 2 and sample 3 are presented in Fig. 3. The loading-unloading-reloading tests for soils were conducted at stress level of 400 kPa, 800 kPa and 1200 kPa, respectively. The results indicate that the slopes of unload-reload for each stress levels are similar to each other. From the results, it is observed that the specimen exhibits non-linear behaviour. This non-linearity decreases in the increase in mean stress. Desai and Siriwardane (1984) reported similar behaviour for tests conducted on an artificial soil. Wathugala (1990) also observed similar behaviour for HC tests on Sabine clay.

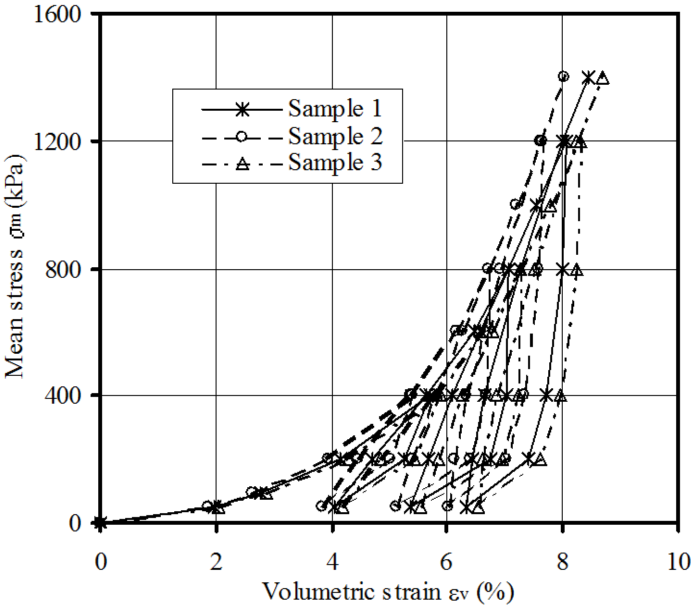

Fig. 3 Mean stress vs. volumetric strain relationship of barind soil.

6 Consolidation Parameters

From the hydrostatic compression tests, consolidation parameters were determined for clay soil. The plots of specific volume versus lnP of three specimens are shown in the Fig. 4. The compression index of the virgin loading curve and swelling index of the unloading-reloading consolidation curve are presented in Table 1. These test parameters can be used in the Cam-Clay model, finite element analysis and settlement calculation for predicting the soil response under various stress conditions.

Table 1. Consolidation constants for normally and overconsolidation barind soil.

Sample types	Normally consolidation line slope (λ)	Overconsolidation line slope (κ)			
		Cycle 1	Cycle 2	Cycle 3	Average value
1	0.036	0.015	0.012	0.013	0.013
2	0.041	0.011	0.014	0.012	0.012
3	0.039	0.012	0.011	0.009	0.011

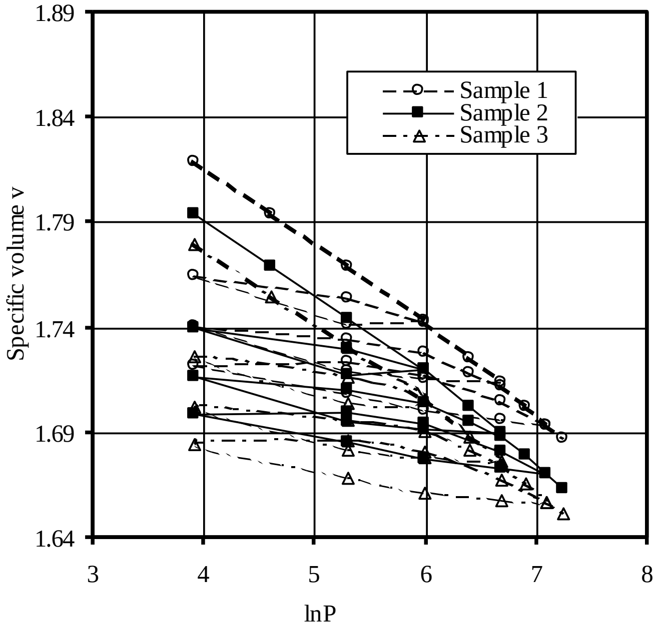

Fig. 4 Specific volume vs. lnP relationship of barind soil.

7 Prediction Vs. Experimental Results For Hc Stress Path

The prediction of the stress-strain characteristics for virgin loading path (Fig.5) can be approximately made using the following relationship

$$\sigma_m = AP_a(\varepsilon_v)^d \tag{2}$$

where A and d are the constants, P_a is the atmospheric pressure, σ_m is the mean stress and ε_v is the volumetric strain. The above two constants can be determined using two sets of known values of σ_m and ε_v. The mean stress-volumetric strain behaviour of the unloading path can also be predicted by shifting the y-axis to a value of ε_o and the corresponding mean stress σ_o. For this case, the equation of the unloading curve can be written as

$$\sigma_o - \sigma_m = A_1P_a(\varepsilon_v - \varepsilon_o)^{d_1} \tag{3}$$

where A_1 and d_1 are the constants. The model constants A, A_1, d and d_1 for clay specimens are presented in Table 2. The predictions of the mean stress versus volumetric strain behaviour for soil are shown in Fig. 5. It is also observed that the predicted stress-strain behaviour is in good agreement with the measured value. Thus, the simple relationship can be used to model the behaviour of clay in HC stress paths.

Table 2. Material constants for unloading and reloading HC stress path.

Sample types	Material constants for HC stress path			
	A	d	A_1	d_1
1	0.096	2.28	0.61	5.08
2	0.10	2.26	0.63	5.19
3	0.11	2.25	0.59	5.30

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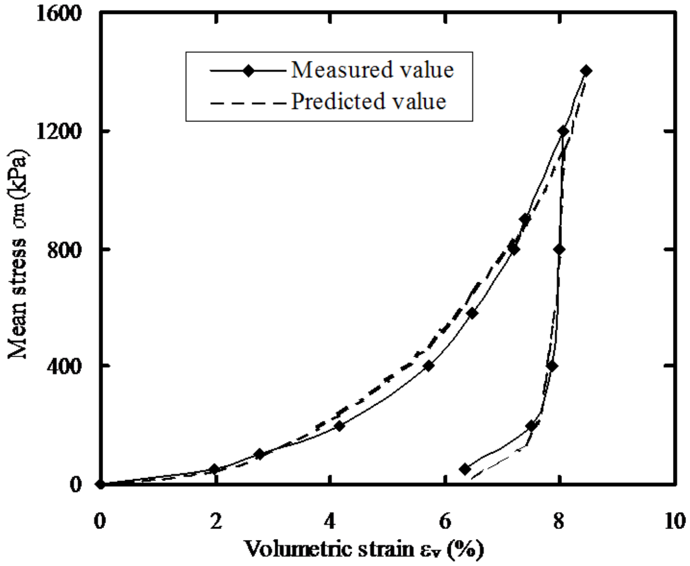

Fig. 5 Measured and predicted behaviour of mean stress vs. volumetric strain for sample 2.

8 Bulk Modulus

The bulk modulus is defined as the change in mean stress divided by the change in volumetric strain and can be approximated from the isotropic consolidation test using the following equation

$$B = \frac{(\sigma_{m1} - \sigma_{m2})}{(\varepsilon_{v1} - \varepsilon_{v2})} \tag{4}$$

where ε_{v1} is the volumetric strain at mean stress σ_{m1} and ε_{v2} is the volumetric strain at mean stress σ_{m2}. Using the theory of elasticity Equations from Lambe and Whitman (1979), the bulk modulus, B, can also be written in terms of the bulk modulus constants. For virgin loading curve

$$B = \frac{(\sigma_{m1} - \sigma_{m2})}{\left[\frac{\sigma_{m1}}{AP_a}\right]^{1/d} - \left[\frac{\sigma_{m2}}{AP_a}\right]^{1/d}} \tag{5}$$

Similarly, the bulk modulus for unloading curve can be expressed as

$$B = \frac{(\sigma_{m1} - \sigma_{m2})}{\left[\dfrac{\sigma_{m1}}{A_1 P_a}\right]^{1/d_1} - \left[\dfrac{\sigma_{m2}}{A_1 P_a}\right]^{1/d_1}} \qquad (6)$$

The bulk modulus of the barind soil specimen was calculated from the virgin loading and unloading curves. From the test results, it is observed that bulk modulus from virgin loading path is smaller than unloading path. The main reason of this behaviour may be due to the difference in volume change which is higher in virgin loading path than that of unloading path. The bulk modulus of virgin loading and unloading path for barind soil are presented in Table 3.

Table 3. Bulk modulus for virgin and overconsolidation barind soil.

Sample types	Bulk modulus kN/m^3			
	Virgin	Average	Unloading	Average
1	30289	29476	90115	88586
2	29541		88389	
3	28598		87254	

9 Conclusions

The hydrostatic compression (HC) test results indicate that the slopes of unload-reloading curve for each stress levels are similar to each other. It is also observed that the mean stress-volumetric strain exhibits non-linear behaviour. This non-linearity decreases in the increase in mean stress. The prediction of the mean stress and volumetric strain characteristics relationships of barind soil for virgin and unloading path are proposed. A consistent set of soil design parameters is obtained by analysis of test results representing bulk modulus and volume change properties as a function of mean stress.

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