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Estimating elastic modulus of California bearing ratio test sample using finite element model

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HIGHLIGHTS

- Present study estimates the elastic modulus of CBR soil sample based on FEM.
- Soil characteristics was modelled by Mohr-Coulomb (MC) model.
- Plaxis 2D can be used to model CBR test satisfactorily.
- Investigation shows acceptance of elastic modulus for further numerical analysis.

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ABSTRACT

Numerical simulation of California bearing ratio (CBR) test needs a set of soil parameters including elastic modulus, Poisson's ratio, stiffness parameters and strength parameters corresponding to soil model. Misestimating of these parameters ends up the simulation into erroneous output. The elastic modulus of soil contained in the CBR mould is difficult to measure due to the mechanics involved in it during test. Present study attempted to estimate the elastic modulus of CBR soil sample based on finite element model (FEM). Plaxis 2D program was used to model CBR test. Parameters involved in the modelling were elastic modulus, Poisson's ratio and shear strength parameters. CBR test and direct shear test were carried in the laboratory for the test soil. Using the regression model and laboratory test results, elastic modulus of the test soil sample was calculated. The validation of the regression and CBR model was carried out by comparing the results of simulation and laboratory test. Coefficient of determination (R^2) of the plot between the results of laboratory test and output of CBR model was found 0.99, which shows the acceptance of elastic modulus for further numerical analysis of the CBR test.

1. Introduction

California bearing ratio (CBR) test was developed by California Highway Department in the year 1930, which initiated the method of incorporating subgrade strength in design of flexible pavement. Since then the test got the popularity in the field of pavement design due its simplicity in performing the test. CBR test is carried out to characterize the subgrade soil in terms of CBR value, which relates stiffness or strength parameter of soil [1,2]. However, the CBR value has no direct use in analysis of pavement structure. Subgrade materials tends to behave elastically due to action of repeated load during its service life and therefore the resilient modulus of subgrade materials is indeed, required for the analysis. Resilient modulus is a measure of elastic modulus based on the recoverable strain under repeated load and can be measured in the laboratory using cyclic triaxial test [3]. However, the apparatus required for the test being complicated, time consuming and expensive, correlations were developed by various researchers to predict resilient modulus from CBR value [4–6]. These correlations are widely popular and are used to design pavement structure around the world [7]. Widespread popularity and application of the test urges better understanding of the mechanics involved in the CBR sample. However, limited number of research has been carried out on the analysis of CBR test [1,7–9]. The probable reason could be the difficulty in evaluating elastic modulus of soil necessary for the analysis of the CBR sample, either by the principles of solid mechanics or modern computational techniques (finite element method, finite difference method, discrete element method etc.). Elastic modulus of soil depends on the condition under which it is measured in the laboratory. It is influenced by confining pressure, dry density, moisture content, soil structure, stress history

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and cementation between soil particles [10,11]. Direct measurement of confinement stress received by the soil sample during CBR test is difficult to measure [12]. Confining stress depends on the magnitude of applied load, gradation and degree of compaction. Araya [13] attempted to measure the confining level received by the granular materials using strain gauge techniques. Measured confining stress may be used as a cell pressure in triaxial test to determine elastic modulus necessary for analysis of CBR sample. However, it raises complexity in the procedure and the error during strain measurement cannot be ruled out. In CBR test, the sample undergoes wide range of stress conditions during loading. Shear failure is observed near to the plunger while further away, only modest amount of stresses are developed [8]. Such stress profiles may not be observed in triaxial test where, deviator stress is raised gradually to fail the cylindrical soil sample under shear. Elastic modulus, therefore, measured by triaxial test may not be appropriate to be incorporated in the numerical analysis of CBR soil sample. In the present study, an attempt was made to estimate the elastic modulus of CBR soil sample through numerical and statistical approach. Following sections describe the methodology followed in the present study.

2. Methodology

The methodology for the present work has been explained in Table 1.

3. Materials

Fine grained soil for the present study was excavated from the area nearby Civil Engineering Department of Tezpur University, Assam, India. Characterization of the excavated soil was done by standard laboratory tests such as sieve analysis, liquid limit test, plasticity limit test, specific gravity test and proctor test. The soil was classified as silt loam based on United States Department of Agriculture (USDA) taxonomy and as clayey-silt of low plasticity as per Unified Soil Classification System (USCS) [14]. Composition and properties of the test soil sample are presented in Table 2.

Table 2
Composition and properties of the test soil sample.

Parameters		Values
Soil Classification	Sand	33
	Silt	54
	Clay	13
Liquid limit, %		35.5
Plasticity index, %		11
Specific gravity		2.61
Modified proctor test		
OMC, %		14%
MDD, g/cc		1.82
Standard proctor test		
OMC, %		16.5
MDD, g/cc		1.72

4. Experimental methods

4.1. Compaction test of soil

Heavy compaction (HC) and light compaction (LC) test were conducted on the soil sample using proctor mould of diameter 150 mm, according to Indian Standard IS: 2720 (Part VIII) – 1983 [15] and IS: 2720 (Part VII) – 1980 [16] respectively. The procedures were further repeated to observe the dry densities of soil corresponding to different compactive effort (CE) and moisture content (MC). Compaction procedure for the required dry densities consists of two conditions. First condition includes compaction of soil using different compactive effort maintaining constant moisture content. Second condition includes dry of optimum and wet of optimum compaction of soil maintaining constant compactive effort. Table 3 shows the detail of the procedure.

4.2. California bearing ratio (CBR) test

CBR test was carried out to investigate the penetration resistance of soil sample, at its different dry densities (obtained from compaction test) as per Indian Standard IS: 2720 (Part XVI) – 1987 [17]. The amount of water and dry soil required to achieve respective dry densities were calculated to mix and compacted in the CBR mould. Procedure of compaction was kept similar to the compaction test (Table 3). Penetration of plunger at a constant rate of 1.27 mm/min was applied to the sample in CBR load frame and the force required against of the penetration of plunger was measured. A graph between loads corresponding to the penetration was drawn from which CBR value (CBR_{LAB}) and the load (F_{LAB}) required for 12.5 mm penetration were observed. The value of CBR corresponding to 2.5 mm and 5.0 mm penetration was calculated from the graph using Eqs. (1a) and (1b) and maximum of it was taken as CBR_{LAB}.

Table 1
Methodology.

Step 1	A finite element model of CBR test (CBR model) was prepared in Plaxis 2D program to calculate load (F_{FEM}) using soil properties as input parameters. Soil properties were elastic modulus (E), Poisson's ratio (ν), cohesion (c) and angle of internal friction (ϕ). There were 68 types of soil samples used for the study. The prepared model was run for each type of soil to obtain the Load (F_{FEM}). Application of the input and output parameters may be summarized as follows in Table 1(a)
Step 2	A multiple regression equation was developed using the input and output parameters of CBR model. Independent variables were E, ν, c, ϕ. Dependent variable was $F_{FEM.}$ Developed regression equation was $E = \frac{F_{FEM} - 1.376\times\nu + 1.015\times c^{0.02} - 1.530\times\tan(\phi)}{3.040\times10^{-5}}$
Step 3	Laboratory tests were carried out to find the F_{LAB}, ν, c and ϕ of test soil sample. Poisson's ratio (ν) was assumed. Included laboratory tests were CBR test (to find F_{LAB}) and direct shear test (to find c and ϕ). Using the laboratory results, E was then estimated from the developed regression equation. (The value of F_{LAB} was input in place of F_{FEM})
Step 4	Using the estimated E value and other parameters (c, ϕ and ν) of the test soil sample, Load (F_{FEM}) is estimated using the CBR model. This calculated F_{FEM} was finally compared with laboratory F_{LAB} for validation of the CBR model

Table 1(a). Input and output properties of CBR model

Sl. no	Soil type	Input properties	Output properties
1	$Soil_1$	E_1, ν_1, c_1, ϕ_1	F_{FEM1}
2	$Soil_2$	E_2, ν_2, c_2, ϕ_2	F_{FEM2}
...	...	....	...
68	$Soil_{68}$	E_{68}, ν_{68}, c_{68}, ϕ_{68}	F_{FEM3}

Note: F_{FEM} is the load obtained from CBR model; F_{LAB} is the load obtained from CBR test.