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Use of an Elastoplastic Framework for the Understanding of the CBR Test for Fine and Coarse Soils

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Abstract. The present paper shows the understanding of factors that influence the value of the CBR test for fine and granular soils. This is important because the CBR test is frequently used in the design and evaluation of pavements. Nowadays, CBR tests are correlated with the resilient module, which is a key parameter in the current mechanistic methods of pavement design. However, the results indicate a large number of correlations depending on the modulus of elasticity and the plasticity indexes of the material that lead to a large dispersion of the results using these correlations. The above indicates that there are several variables that have not been taken into account in the correlations. The purpose of this study is to show how the value of the CBR test is a function of other variables such as the size and shape of the particles, the crushing, the compaction energy and the elastic behavior of the material. These variables were evaluated through FEM (Finite Element Method) simulations while varying several geotechnical parameters known in practical geotechnics. These simulations in FEM include a linear elastic model, a failure criterion (elastoplastic model), with isotropic hardening, in addition these were prepared for granular and fine soils. The results show that the CBR depends not only on the Young's modulus (a parameter commonly used to correlate with the CBR), but also seems to depend on the compressibility due to the crushing of particles and the energy of compaction. Finally, this paper provides ideas that improve the understanding of the variables that lead to high or low CBR values for fine and granular materials.

Keywords. CBR test, fine soil, granular soil, geotechnical parameters, energy compaction, crushing.

1. Introduction

The CBR test was created in 1920s. Since then, it has been one of the most used tests for the quality evaluation of a pavement layers. This test has been implemented in several standards and design methodologies, among which are the Experimental Center for Research and Study of Building and Public Works guidelines (CEBTP, 1980, 1984) [1; 2] used for road design in French speaking tropical Africa; the American Association of State Highway and Transportation Officials (AASHTO) [3], among others. In addition,

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the value of the CBR Test is generally correlated with the resilient modulus [1-5]. One of the reasons to correlate this value is that the resilient modulus is a key parameter in modern mechanistic pavement design. However, the correlation between the module and the CBR is not linear [3-5]. Also, other factors are involved in this relation, [4-7]. This paper seeks to understand what factors influence the relation of the CBR value and the elastic modulus. This was done for fine and granular soils.

A better analysis of the factors that influence the CBR was made by means of Finite Element Method (FEM) simulations. These simulations were made to change various geotechnical parameters known in practical geotechnicsd. These FEM simulations were used with a linear elastic model and the Drucker–Prager yield criterion. FEM simulations simulated soils in drained conditions and undrained conditions. From these simulations the parameters that influence the CBR value were obtained.

The results show that CBR is a function of Young's modulus which is commonly correlated with the CBR. However, the CBR is also function of compressibility due to compaction energy, permeability, compressibility due to particle crushing and the drainage condition. The influence of these factors depends on the type of material. Also, this study provides some insights that improve the understanding of variables that result in either high or low CBR values.

2. CBR test

The test consists of the indentation of a normalized piston of 5 centimeters (diameter) at a ratio of 1.25 mm/min, in a soil sample. The sample of compacted soil was made in the CBR mold (cylindrical model of the 17.78 cm height and diameter of 15.2 cm) and it compacted to the energy of the modified Proctor test. Subsequently, the stress readings are obtained at a 2.5 mm and 5 mm of penetration, then which these readings are compared with the standardized stresses that were for a limestone in California [2, 4]. The comparison between the two readings is given as a percentage and that is the value of the CBR test. Figure 1 shows some equipment used in the CBR test.

Figure 1. The CBR mold and implements in the CBR Test.

In the present paper, the CBR value was calculated for a penetration of 2.5 mm. The standard stress of the test for this penetration is 6900 kPa. In addition, the simulations in FEM were done taking into account an additional load of 4.5 kg that simulates the load imposed by the pavement structure.

3. Constitutive model

The constitutive model selected for simulation in the FEM was a lineal elastic model with a Drucker-Prager criteria and an elliptical cap (Figure 2). This model is very popular in geotechnical engineering [5, 8, 9]. In the elastic range, the model has two parameters: Young's modulus E and Poisson's ratio μ. In addition, in the elastoplastic range the parameters are divided in two parts. The first part are parameters of the criterion, in this case the parameters are: β = the friction angle and d = cohesion in the p-q plane (Figure 2). These parameters are equivalent to ϕ = the friction angle of the soil, and c = cohesion of the soil in the Mohr Coulomb model. The second part are parameters with the cap. In this case, these parameters are a function of the compressibility of the material. The cap parameters are the eccentricity of the cap ellipse R, and a constant K that controls the shape of the yield surface in the plane π. Another important variable is p_p which is a state variable giving the evolution of the isotropic compression law of the material (which controls hardening–softening). This stress corresponds to the yield point in the isotropic compressibility line. The evolution of the plastic volumetric strain (Eq. (1)) is a function of the slope of the virgin isotropic compressibility line λ (considered in the plane of the void ratio e and the natural logarithm of p), κ (the slope of the unloading–reloading line of the material), and e_0 (the initial void ratio). In addition, all parameters can easily be obtained from the triaxial tests and isotropic consolidation.

$$\varepsilon_v^p = \frac{\lambda - \kappa}{1 + e_0} \ln \frac{p}{p_p} \tag{1}$$

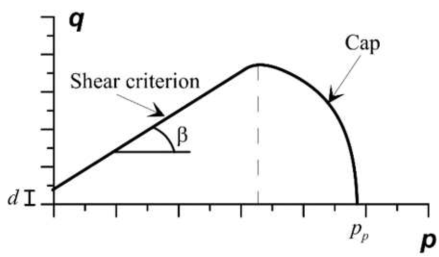


Figure 2. Scheme of the yield surface in the Drucker and Prager model with cap [4, 9].

4. Model for finite element method (FEM)

The simulations in the FEM were made in the ABAQUS software. The geometric stage was the first stage of the constructed model. This geometry has the dimension of the mould of CBR test (cylindrical model of the 11.65 cm height and diameter of 15.2 cm). The second stage was to select the constitutive model of the material; this model was shown in the previous section. The third step was the boundary conditions; the boundary conditions were the roller condition on the lateral side and fixed condition in the model base. The fourth step was the mesh of the model. The meshing used the C3D8P (continuous, eight nodes with pore pressure measurement) element. These elements were used in the fine soil and granular soil. However, the difference between model to fine soil and granular soil is the permeability of the material. The fifth step was the creation of sequential stages of the load: the first imposed 4.5 kg on the surface of the model (pavement construction) and second imposition of strain of the piston on the surface of the model until there was a total displacement of 12.5 mm. Figure 3 shows the schematic model of CBR.

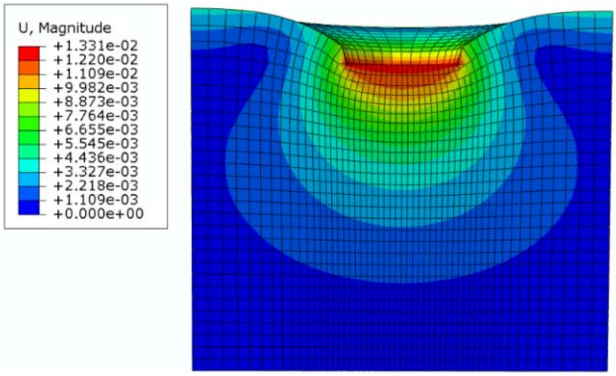


Figure 3. Finite Element model for the CBR test.

5. Results of the simulations in the FEM and discussion

FEM simulations were made with the typical parameters of granular soil and fine soil; the materials selected were a crushed hornfels rock and kaolin. The parameters used in the present paper are shown in Table 1 and Table 2. These parameters were obtained from research by Araya [10]; Hight and Stevens [11]; Bolton, Britto, Powrie and White [12]; Mendoza and Caicedo [4, 5].

Table 1. Parameter used to the simulation to granular soils from Araya [10].

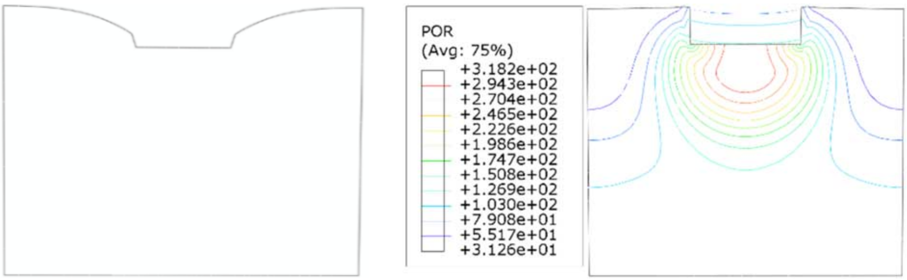
E	c	ϕ	ν	e_0	λ	κ	p_p
kPa	kPa	°	-	-	-	-	kPa
200,000	108.5	52.4	0.3	0.3	0.1	0.02	7000

Table 2. Parameter used to the simulation to fine soils [5, 11-13].

E	c	ϕ	ν	e_0	λ	κ	p_p
kPa	kPa	°	-	-	-	-	kPa
8,000	10	23	0.34	0.8	0.18	0.03	400

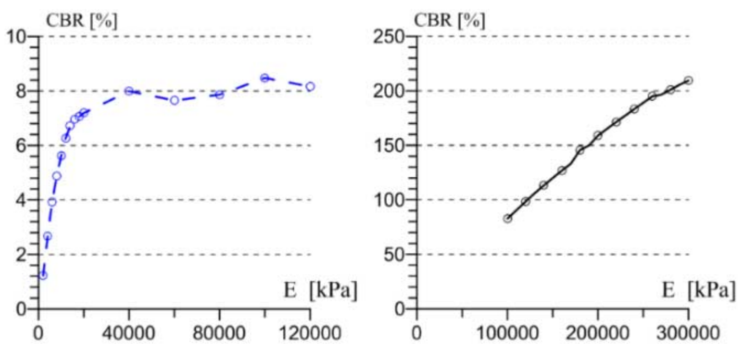
The first results were to observe the generation of pore pressure in the model, as shown in Figure 4. From this figure, a pore pressure equal to zero was obtained in the model of granular material and high pore pressure in the model of fine soil. The difference between models was the permeability because the model of fine soil has 1.80E-09 m/s and the model of granular material has k=0.1 m/s. This is important because the CBR test does not have control of the initial condition of drain (drained and undrained condition). The granular soil has a drained initial condition and the fine soil has an undrained initial condition.

Nowadays, transportation geotechnics have many correlations to the CBR value and the elastic modulus. These correlations are used in fine soil and granular soil. For this reason, the paper shows a sensitization of Young's modulus and the CBR value to fine soil and granular soil, as shown in Figure 5. Simulations show an increase of the CBR value with increase to the Young's modulus in the two cases. However, the American Association of State Highway and Transportation Officials (AASHTO) [3] and Mendoza and Caicedo [4] also show this correlation is not linear, as is shown in Figure 5a. Another characteristic shown in Figure 5a was the change of stiffness after a module of 40000 kPa. This can be important because the most popular correlations are a lineal relation between the Young's modulus and the CBR, as the papers by Nielson [14]; Heukelom and Klomp [15] and French Experimental Center for Research of Building and Public Works (CEBTP) [1]. These correlations have values of slope changing from 1800 to 10340 and these slopes have units in kPa. On other hand, the change in CBR values was from 1.6% to 8% in the fine soil and in the case of the granular material, the change was from 82% to 220%, in relation with the change of the Young's modulus.



(a) (b)

Figure 4. Pore pressure generated in the Finite Element model for: (a) model of granular material; (b) model of fine material.

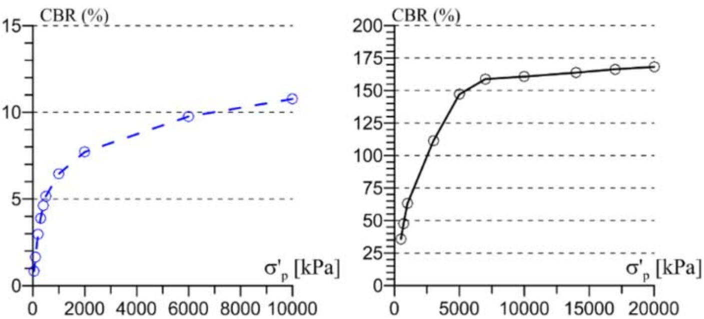


(a) (b)

Figure 5. Effect of elastic modulus for: (a) model of fine material; (b) model of granular material.

Analyses of the friction angle ϕ and the cohesion c are not presented. The reason was that these parameters did not show a tendency, in the sensitive analyses of the parameters. In conclusion, these parameters are not very important to the CBR value.

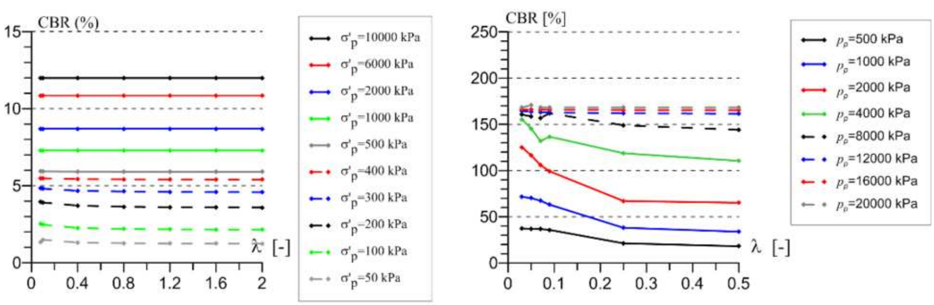
The mean yield stress on the isotropic compressibility line (p_p) is a useful parameter for describing compressibility of FEM model. In addition, the researches presented by Sreelekshmypillai and Vinod [16]; Mendoza et al. [17]; Horpibulsuk et al. [18]; Gurtugand Sridharan [19] have shown that, for fine soils, the yield stress during compression depends on the compaction energy in the CBR test. In the case of the granular material, the mean yield stress on the isotropic compressibility line (p_p) is a function of the crushability of the material, which in turn depends on the shape of the particles, their strength, and grain distribution, as was shown in the paper by Mesri and Vardhanabhuti [20]. The paper of Mesri and Vardhanabhuti [20] defined of the mean yield stress with the point at which the slope of the compressibility curve changed (the point of maximum curvature). From this research, it is shown that the mean yield stress may vary from 500 kPa for an angular biogenetic carbonate sand to nearly 40000 kPa for a well-rounded quartz sand. Figure 6 shows the influence of the mean yield stress in the CBR value in the two cases studied this parameter is very important in the CBR value. In the fine soil, the CBR value increased from 1% to 11% and these values were obtained, p_p=50 kPa and p_p=10000 kPa. The increase of granular material was from 33% to 170% and these values were obtained, p_p=500 kPa and p_p=20000 kPa.



(a) (b)

Figure 6. Changed of the yield mean stress in the Finite Element model for: (a) model of fine material; (b) model of granular material.

The parametric analysis of the compressibility parameters (mean yield stress p_p and compression index λ) is depicted in Figure 7. Figure 7a, of fine soil, shows a low influence of compression index on the CBR, on the contrary, the yield stress has a high influence on the CBR value. The high effect of the yield stress was preserved in the granular soil. However, this effect is less important with the increment of yield stress. Figure 7b additionally shows a decrease of the CBR value with the increase of the compression index. All cases studied have an influence on the cap of the model because the cap is controlled by mean yield stress (p_p). On the other hand, the compression index only was important to low values of the yield stress. An explanation is that the compression index only works when the stress paths touch the cap. In addition, high values of the compression index produce high volumetric strains equal to large vertical displacements and reduce the CBR values.



(a) (b)

Figure 7. Sensitization of compression parameters for: (a) fine soil; (b) granular soil.

The results of elastoplastic simulations are represented in Table 3. This table shows the relative relevance of geotechnical parameters studied in the present paper. For example, the Young's modulus is not the only parameter that controlled the CBR value. The Yield stress for compressibility has an important relevance to the CBR value in granular soils and fine soils. The compression index only has importance in the granular material and this parameter was not important in fine soil. The parameters of shear resistance do not have important relevance for the CBR values. Therefore, the correlation of the CBR value and elastic modulus should have the yield stress. In addition, a special correlation in the granular material can be the influence of the compression index.

Table 3. Parameter influence and state variable influence on the CBR to fine soil and granular soil.

Characteristic	Effect on the CBR		Comments
	Fine Soil	Granular Soil	
Cohesion (c)	↔	↔	Only very high values of cohesion significantly move the failure criterion and the CBR.
Compression index (λ)	↓	↓	High values of compression index give low values of CBR for granular soils. In the fine soil it is important only to low yield stresses. This is a function of particle size, shape and void ratio.
Friction angle (φ)	↔	↔	The friction angle was found to have only a small effect on compacted materials with high friction angles.
Yield stress for compressibility (p_p)	↑	↑	The yield stress for compressibility is very relevant at low values, but its importance falls as its value increases. This is a function of particle fracturing and splitting, and particle rearrangement for the granular soil, in the fine soils is function of geological history.
Young's modulus (E)	↑↑	↑↑	CBRs change a great deal in response to changes in the elastic modulus, but this relation is not linear, mainly in the fine soils.

Note: ↑↑ indicates a parameter that substantially increases the CBR. ↑ indicates a parameter that increases the CBR. ↔indicates a parameter that is not relevant for the CBR. ↓ is a parameter that lowers the value of the CBR.

6. Conclusions

Simulations with an elastoplastic model were able to represent the fine soil and granular soil. Based on the results, the simulations showed that the CBR value depends not only on the Young modulus but also on the compression parameters such as yield stress for compressibility and compression index; these parameters depend on if the condition is drained or undrained. In addition, the CBR is a function of compressibility due to compaction of energy, permeability and compressibility due to particle crushing.

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