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Numerical simulation of CBR test and HS-Small parameter characterization for Bogotá soils

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Abstract
This paper presents the determination of HS-Small constitutive model parameters for the Sabana Formation, the major deposit of Bogotá city. Mechanical parameters were obtained from index parameter of physical characterization, using correlations consulted as state-of-the-art. The characterization obtained has been validated with a numerical model of the CBR test, showing good agreement with typical values in the City of Bogotá. The methodology presented here would make possible the determination of the HS-Small parameters for the entire profile of the Sabana Formation. Once the parameter sets of the samples have been validated, a parametric analysis is performed, varying the friction angle and the shear module values. This parametric study shows that for the HS Small constitutive model, the stiffness modulus has a greater contribution in the CBR test than the friction angle, which would support the correlations between the resilient modulus and the CBR value; correlations widely used in pavement engineering. The methodology of characterization presented here would make possible the determination of the HS-Small parameters for the entire profile of the Sabana Formation. This allows for the numerical simulation of complex geotechnical works in the early stages of design when advanced mechanical laboratory tests are not available.

Keywords: FEM; HS-Small; CBR; diatomaceous soils; numerical model

Simulación numérica del ensayo CBR y determinación de los parámetros del modelo HS-Small para los suelos de Bogotá

Resumen
En este artículo se presenta la determinación de los parámetros del modelo constitutivo HS-Small para la Formación Sabana, el depósito más importante de la ciudad de Bogotá. Los parámetros mecánicos se obtuvieron a partir de propiedades índice de caracterización física, utilizando correlaciones consultadas del estado del arte para los suelos de Bogotá. La caracterización obtenida ha sido validada con un modelo numérico del ensayo monotónico de CBR, mostrando buena concordancia con valores típicos en la ciudad de Bogotá. La metodología aquí presentada haría posible la determinación de los parámetros HS-Small para todo el perfil de la Formación Sabana. Una vez validados los parámetros, se realizó un análisis paramétrico del modelo CBR variando los valores del ángulo de fricción y del módulo de corte. Este estudio paramétrico muestra que para el modelo constitutivo HS Small, el módulo de rigidez tiene una mayor contribución en el resultado del ensayo CBR que el ángulo de fricción, lo que sustentaría las correlaciones entre el módulo resiliente y el valor CBR; correlaciones ampliamente utilizadas en ingeniería de pavimentos. La metodología de caracterización aquí presentada haría posible la simulación numérica de obras geotécnicas complejas en las primeras etapas de diseño cuando no se disponga de ensayos mecánicas avanzados de laboratorio.

Palabras clave: FEM; HS-Small; CBR; suelos diatomáceos; modelo numérico

1 Introduction.

Numerical simulations are fundamental methods for understanding the phenomena within the geotechnical analysis of earthworks and other civil projects. Numerical simulation is not approximate by itself, rather, it is an implicit theoretical tool that aims to solve an engineering problem using an approximate method. The complexities of numerical

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modeling make its implementation highly simplified, but the same is true for laboratory techniques and full-scale models in the field. Therefore, numerical methods and constitutive models have limited effectiveness and precision [1-2]. The same occurs with measurement devices used in laboratory and field tests. The constitutive equation is a key topic for the development of satisfactory numerical modeling. In geotechnical engineering, constitutive models might consider several features of the mechanical behavior of soils. Soils have properties such as stress and strain path dependence, the anisotropy of stiffness and strength, and the nonlinearity of the stress-strain relationship, which are properties commonly present in concrete and wood. However, soils also exhibit other very particular properties such as pore pressure generation, plastic deformation associated with friction by deviatoric and isotropic components, and the viscous effects associated with the speed of load application [3].

In Geotechnics, one of the advanced constitutive models available is the Hardening Soil Model or HSM. This constitutive model is offered in several commercial software packages such as PLAXIS, FACE2, Z-SOIL. The HSM incorporates the non-linearity of stiffness through a hyperbolic law and allows plastic deformation for both deviatoric and isotropic stresses [4]. This constitutive soil model was improved in 2007 when the Matsuoka-Nakai surface was introduced as a failure criterion due to a deviatoric stress component and the plastic flow rule was modified to incorporate stiffness criteria associated with small deformations, resulting in an enhanced model called the HS-Small model [5].

This paper presents the numerical modeling of a CBR test implemented with the HS-Small model included in the PLAXIS 2D software, with specific parameters for the diatomaceous soft soil of the city of Bogotá. The characterization of the model parameters was performed following the correlations presented by other authors for the soils of the city [6-7]. The results of the numerical modeling were contrasted with typical results of CBR tests, showing good agreement. To summarize, it can be inferred that the HS-Small parameters used in this study accurately represent the surface soils of Bogotá. Therefore, the variations of this set of parameters, which were adjusted following the criteria presented in this paper, could be used for modeling more complex geotechnical works such as the foundation of tall structures and deep excavations, as in the case of the city subway and other major projects. The work also delves into the discussion of the correlation between the resilient modulus and the CBR value. Through a parametric analysis where the friction angle is varied by 10 % and the stiffness modulus degradation curve by 10 %, it was found that the friction angle has an insignificant weight in the executed CBR models. In contrast, raising or lowering the modulus degradation curve by 10 % generates variations of up to 7.3 % of the original CBR value.

2 CBR test and its numerical simulation

In the 1930s, the former California Highway Agency had already included the test known today as the California Support and Expansion Ratio – CBR test as a routine test for the characterization of roadway and subgrade materials. The CBR test consisted of the penetration of a soil-material sample embedded in a metallic mold with a 3-square-inch piston at a speed of 0.05 inches per minute. Originally, the test was developed for the characterization of untreated crushed granular materials, which are indifferent to the typical tests at that rate such as the liquid limit, plastic limit, and shrinkage. The rapid reception of the test was due to the publication of easy-to-apply specifications, such as considering a granular base with a minimum support value of 80 % as acceptable. The early California Highway Agency would support its specifications in case studies where surface roughness and cracking of the treated surface course were clearly correlated with the CBR values of the subgrade [8].

Originally, the California method of design for pavements consists of designing charts to select the total thickness of the pavement for a tire load of 7,000 and 12,000 pounds from the CBR value of the subgrade. From the design of these charts, the US Corps of Engineers made theoretical extrapolations for typical aircraft loads for World War II runway construction. The improvement was favorable in civil infrastructure due to the increase in the number of vehicles in the following decades. In those years, the criterion that accepted the load ratio at 0.1 inches as the value of CBR was incorporated, unless the value at 0.2 was greater [9]. Currently, the CBR procedure is standardized by the AASHTO T-193 and ASTM D1883 standards. For Colombia, the INV E-148 standard applies. Philosophy and procedure remain the same: sample in 6-inch mold, 3-inch square flat nose piston area penetrating at 0.05 inches/min. During the test, the load must be collected at different penetrations up to 0.3 in. and the sample is tested at natural humidity (optimal in the case of compaction) and at the humidity acquired after a period of immersion during which the swelling or expansion of the material is also recorded [9].

Hight and Stevens [10] carried out a numerical study to investigate the impact of stiffness parameters on the response of clays during a simulated CBR test. The researchers employed a non-linear undrained elastic model (Poisson 0.499) varying the magnitude of the stiffness and resistance parameters. The sensitivity analysis showed that the CBR value was strongly correlated to the undrained shear resistance, and therefore, researchers concluded that the CBR test does not reflect the stiffness of saturated clays. The geometry of the used model was selected as large as possible to avoid boundary constraints as in bearing capacity problems. In fact, Finite Element models have been applied in several investigations focused on numerical simulations of small-scale bearing capacity tests, as these physical tests have strong similarities with CBR since they involve small-sized loads applied on the surface and they are strain-driven tests. The agreement between physical and numerical tests shows that the Finite Element Method is an ideal tool for simulating CBR tests as long as bearing capacity problems [11-12].

Improved Finite Element models with the detailed geometry of the CBR test, including the mold borders and the overload, have also been implemented for CBR studies as a mechanical test. Currently, several studies include both monotonic and cyclic loading. In the case of monotonic load, it is remarkable the work presented by Narzary & Ahamad [13]. The researchers ran 68 drained simulations of CBR tests incorporating the mold thickness and the annular surcharge disc, whose materials were considered linear elastic, while the soil inside the mold was a linear elastoplastic model with Mohr-Coulomb criterion without hardening. The numerical modeling allowed researchers to find a multivariable nonlinear regression (involving friction angle, cohesion, Poisson's ratio, among other parameters) that predicts the linear elastic modulus of the sample. The equation was validated with laboratory tests showing good correspondence between the load value measured in the laboratory and that estimated in the numerical multivariable equation considering values of the resistance parameters previously estimated with direct shear tests [13].

One of the concerns in CBR testing is the draining condition during plunger penetration. In fact, the test presents heterogeneous boundary conditions (it is a boundary value problem), so the distribution of stresses and strains is not uniform within the sample. This situation implies a temporal and spatial variation of the excess pore pressure produced by the piston (and also an evolution of the degree of saturation). As is generally accepted, water flow is controlled by the permeability, which depends on several parameters such as the anisotropy of the fabric (and its evolution), the granulometry, and the void ratio. Therefore, the water permeability depends on the type of soil and the loading process itself.

Recently, Mendoza & Caicedo [14] conducted a sensitivity study of the CBR test considering drained or undrained conditions using a Finite Element numerical model. The researchers applied an elastoplastic constitutive model with a Drucker-Prager surface controlling plasticity by deviatoric loading and an elliptical cap that controls spherical compression deformation (known as the Drucker-Prager elastoplastic cap model). The results showed that for permeabilities lower than 10-6 m/s, the CBR value was influenced by the excess pore pressure located below the piston. The researchers also found that the CBR numerical model varies slightly with cohesion and friction, but it is very sensitive to pre-consolidation pressure [14].

3 Brief description of lacustrine soils of Bogotá

The largest geological deposit in the city is called the Sabana Formation. The geographical context for the city is presented in Fig. 1.

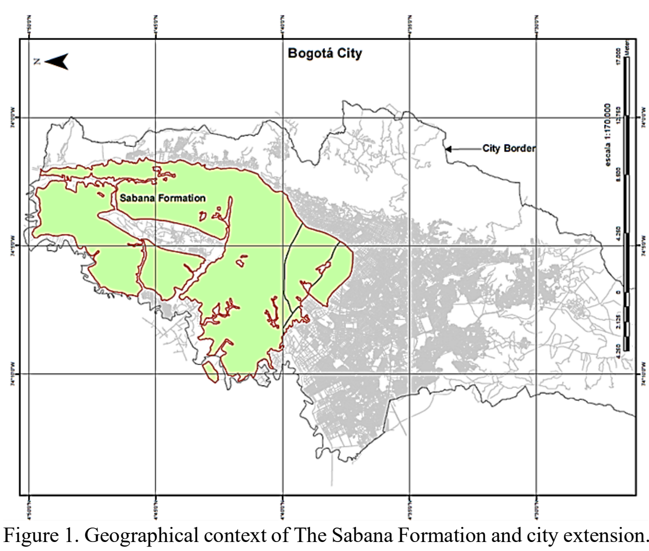

Figure 1. Geographical context of The Sabana Formation and city extension.
Source: Authors.

Table 1.
Typical values of CBR undisturbed samples from Bogotá city.

CBR range (%)		Amount	Percentage	Accumulated
0.10	0.99	3	4 %	4 %
1.00	1.99	7	10 %	14 %
2.00	2.99	25	36 %	50 %
3.00	3.99	17	24 %	74 %
4.00	4.99	11	16 %	90 %
> 5.00		7	10 %	100 %

Source: Modified from Bojacá-Torres [15].

A large portion of the city is built over this Formation. According to the modern interpretation, and to generate a synthetic stratigraphic profile, this study summarizes the lithostratigraphy of the Sabana Formation as follows: from 0 to 5 meters deep, there is soil with less than 10 % organic matter, the plastic limit of 33 %, humidity of 80 % and the liquid limit of approximately 110 %. From 5 to 80 meters deep, there are unconsolidated lake sediments with a high proportion of organic matter and a very soft consistency, with a liquid limit of 140 %, water content of 70 to 140 %, and a plastic limit between 40 to 50 %. These two layers can be associated with shallow lacustrine deposits in which there was a strong presence of diatoms which are presented today as fossils that change the mechanical properties of the soil. Despite the high plasticity of these deposits, it can be noted that the Sabana Formation generally exhibits high plasticity but low clay content, and a high friction angle, both characteristics of diatomaceous soils. From 80 m, the lacustrine deposit continues with soils having less than 10 % of organic matter, a liquid limit of about 90 %, and a soft consistency ($0.5 < IC < 0.75$). In the western and northwestern parts of the city, in areas near the Bogotá river, the Sabana Formation can reach 500 m depth. In general, the water table can be found between 5 to 7 m deep. Regarding mineralogy, The Sabana Formation has kaolinite, vermiculite, illite, and fossilized diatoms. Recent publications have shown that the mechanical properties of the Sabana Formation are highly correlated with the physical properties using particular correlations.

For the city of Bogotá, several CBR-test reports can be found in public government databases. These databases have contributed to the execution of investigations such as Bojacá Torres, [15], where a series of 70 tests extracted from these databases is compiled and processed. In this study, only CBR tests that were executed on samples form The Sabana Formation were selected. Consequently, Table 1 shows some typical results from CBR tests performed on undisturbed samples extracted from different areas all over The Sabana Formation in the city of Bogotá.

4 HS-Small parameter determination

The HS-small model is developed within the theoretical framework of the theory of plasticity. The HS-small model consists of an extension of the HS model, by incorporating the degradation curve of the stiffness modulus. Both models consist of the extension of the non-linear Mohr-Coulomb failure criterion through a cap-model failure surface [3–5].

Mechanical behavior of soil is complex. Without

Table 2.
Typical (median) physical properties of superficial Sabana Formation soils.

Sample	LL (%)	OCR	LOI (%)	Ic
#1	120.0	5.0	10.0	0.70
#2	100.0	5.0	10.0	0.60
#3	80.0	6.0	10.0	0.70
#4	90.0	4.0	10.0	0.60
#5	90.0	5.0	10.0	0.50

Source: Authors.

considering solid-water phase interaction, features such as the nonlinearity caused by stress-dependent stiffness, modulus degradation by overstraining process, pre-consolidation stress memory, and non-associative plastic flow rule (related to anisotropy) are some of the most important characteristics to be considered in the numerical simulation of geotechnical problems. Another aspect is the load-failure criteria that are directional and time-dependent [16].

In this study, numerical simulations were performed with PLAXIS 2D software employing the HS-Small constitutive model. HS-Small is an elastoplastic model which incorporates nonlinearity as an elastic hyperbolic law, frictional and cap hardening to model plastic strains, and a law for modelling the decay of small-strain soil stiffness [5]. The constitutive model allows stress-dependent stiffness for loading and unloading in the elastic range until Matsuoka – Nakai yield criterion is reached. Efforts have recently been made to obtain the parameters of a similar constitutive model, such as the case of determining the parameters of the Hardening Soil model for tropical soils in the city of Brasilia [17].

HS-Small parameters might be calibrated from the Drained Triaxial Test and Consolidation test performed on undisturbed samples. However, mechanical properties can be estimated from index characteristics if well-established correlations are available for the particular site. Therefore, in this paper, HS-Small parameters are estimated from novel correlations for Bogotá soils [6-7].

For the numerical simulations, five synthetic samples were used. For this study, it is considered that the parameters presented in Table 2 are enough to determine most of the parameters of the HS-Small constitutive model. Considering that the water table would generally be below 7 m, all the synthetic samples are full unsaturated (dry).

Other considerations are the typical values of shear wave velocity V_s. For instance, the following profile by zones was considered: from 0 to 7 m deep, the average wave speed is V_s=100 m/s, from 7 to 15 m it drops to about 80 m/s, between 15 and 25 m it returns to 100 m/s, to rise to 125 m/s before 35 m and jump to 150 m/s from this depth [18].

The drained friction angle is obtained from eq. (1), proposed by B. Caicedo et al. [6]. The latter is calculated from eq. (2), a correlation proposed by Caicedo et al. [7].

$$\phi' = 18.5 + 0.112LL \tag{1}$$

$$S_u = P_{atm} \times PI \times w^{-1.8} \tag{2}$$

From the friction angle and the preselected over-consolidated ratio, the earth pressure coefficients at rest are evaluated using eq. (3) and eq. (4), as suggested by Kulhawy & Mayne, [19].

$$K_{0SC} = (0.95 - \sin\phi)\sqrt{OCR} \tag{3}$$

$$K_{0NC} = 0.95 - \sin\phi \tag{4}$$

Gravimetric parameters as soil unit weight and void ratio are obtained using specific gravity estimated from eq. (5), a correlation proposed by Caicedo et al. [7].

$$G_s = 2.68 - 0.019LOI \tag{5}$$

The wet unit weight, the void ratio, and the water content must be adjusted to ensure that the low strain shear modulus correspond to a shear wave velocity near 100 m/s, as noted above. With the above parameters and the average depth of the sample, the shear modulus at low deformations can be calculated by eq. (6). To evaluate horizontal effective stress, it is necessary to consider that for soils above the water table in Bogota, OCR is greater than 2 with occasional maximums close to 7.

$$G_0 = \frac{(10-e)^2}{(1+e)} \times 8.76P_{atm}\left(\frac{\sigma'_3}{P_{atm}}\right)^{0.49} \tag{6}$$

The shear modulus degradation model is obtained according to eq. (7).

$$\frac{G}{G_0} = \frac{1}{1+\alpha|\gamma|^{\lambda}} \tag{7}$$

Where λ=0.173·$LL^{0.34}$ and α=191.2$\lambda^{2.19}$, and γ is the shear strain, another mechanical parameter of HS-Small is the shear strain at 70 % of G_0 or $\gamma_{0.7}$. Making G/G_0 = 0.7, eq. (7) leads to eq. (8).

$$\gamma_{0.7} = \left[\frac{1}{\alpha}\left(\frac{1}{0.7}-1\right)\right]^{-\lambda} \tag{8}$$

The degradation of moduli for each sample is evaluated using eq. (6) and eq. (7), and those index parameters presented in Table 1. Then, the degradation of moduli is presented Fig. 2.

Shear moduli at large deformation G may be evaluated using eq. (6) considering a strain value of γ=0.04. Therefore, Young modulus at large strain levels E_{50} is estimated using eq. (9) considering a Poisson ratio ν=0.4. Although the Poisson's ratio can be variable during straining process and highly scattered, recent analyzes show that for saturated soils (e.g. without suction) the values of Poisson’s ratio are the highest and relatively constant under lower scattering [20].

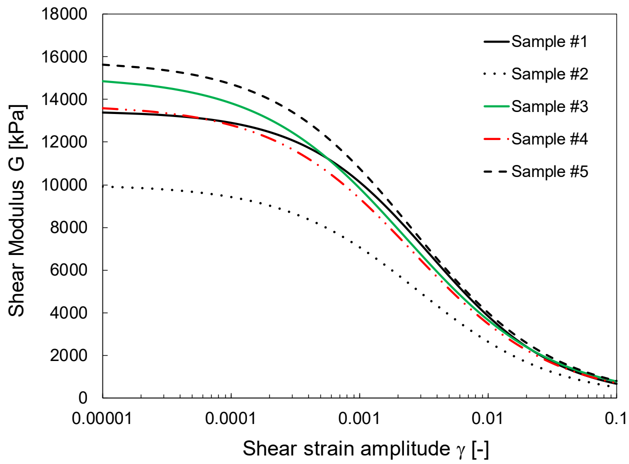

Figure 2. Shear degradation model for synthetic samples.
Source: Authors.

$$E_{50} = 2G(1 + 2v) \tag{9}$$

The initial elastic or unloading Young modulus Eur might be settled near to the model-default-value according to eq. (10).

$$E_{ur} = 2.1 \times E_{50} \tag{10}$$

The reference edometric modulus can be estimated using eq. (11), considering a vertical effective pressure of σ'_v=100 kPa.

$$E_{edo} = \frac{2.3(1+e)}{C_c} \times \sigma'_v \tag{11}$$

Compression index may be correlated using eq. (12), a correlation proposed by Caicedo et al. [7].

$$C_c = 0.01(LL - 0.58) \tag{12}$$

From the above the strength and deformation parameters for the HS-Small constitutive model from the five samples are presented in Table 3 and Table 4.

Table 3.
Strength parameters evaluated for samples.

No.	IP %	w %	γ kN/m³	γ_{sat} kN/m³	e -	S_u kPa	ϕ' °	cut-off kPa	K_0 -
#1	82	93	13.41	14.03	2.6	33.19	31.9	12.44	0.94
#2	67	80	11.85	13.81	2.8	35.56	29.7	12.63	1.02
#3	51	60	13.8	15.05	1.9	45.43	27.5	16.61	1.2
#4	59	71	13.8	14.72	2.1	38.82	28.6	12.06	0.94
#5	59	75	14.59	14.88	2	35.17	28.6	12.15	1.05

Source: Authors.

Table 4.
Strain-Stress properties estimated for samples.

No.	λ –	α –	σ'_3 kPa	G_0 kPa	G kPa	Cc -	VsZ m/s	G/G_0 -
#1	1	145	44.2	13463	1417	1.19	100	10.50%
#2	1	126	30.1	10006	1021	0.99	91.9	10.20%
#3	1	107	24.8	15086	1500	0.79	105	9.90%
#4	1	117	26	13749	1384	0.89	99.8	10.10%
#5	1	117	30.8	15816	1592	0.89	104	10.10%

Source: Authors.

Table 5.
HS-Small strain-stress parameters for superficial Bogotá soils.

No.	G_0 (kPa)	v -	E_{edo} (kPa)	E_{ur} (kPa)	E_{50} (kPa)	$\gamma_{0.7}$ –
#1	13463	0.4	1600	8333.1	3968	0.0014
#2	10005.6	0.4	1012	6003.5	2859	0.001
#3	15086	0.4	1934	8822.1	4201	0.0008
#4	13749.4	0.4	1705	8136.9	3875	0.0009
#5	15815.8	0.4	1965	9359.8	4457	0.0009

Source: Authors.

Thus, the required HS-Small moduli are presented in Table 5.

5 Numerical model and results

An axisymmetric model of the CBR molding was created in PLAXIS 2D using basic dimensions in millimeters. The thickness and material of both the mold and the upper angular ring were taken into account. The mold has an external diameter of 162.4 mm, with a thickness of 6 mm, while the charging ring has a thickness of 5 mm. The materials assigned for these elements were considered linear elastic and non-porous with Young's modulus of 110 and 200 GPa respectively, and a Poisson's ratio of 0.35 for both of them. An interface element of 0.75 value was considered for the soil-metal contact. In the numerical model, the soil sample has a diameter of 152.4 mm and a height of 172.8 mm. The modeling was performed in a drained regime with the soil inside the mold completely dry. The displacement-driven numerical test was performed until a displacement of 5.08 mm was reached uniformly at the piston area.

The triangular element of 15 nodes was used. The mesh was refined until a smoothed stress and strain distribution within the model was found. A total of 759 elements and 6433 nodes were adjusted using the automatic grid step. Fig. 3 presents the numerical model implemented in PLAXIS 2D.

Fig. 4 presents a heat map of the typical displacement distribution taken at the final stages, i.e. piston penetration over 5.08 mm. Both vertical and horizontal distribution show smooth zones thorough the sample. It is clear that beneath the piston, the vertical displacement is concentrated, which generates a vertical-displacement bulb of one piston

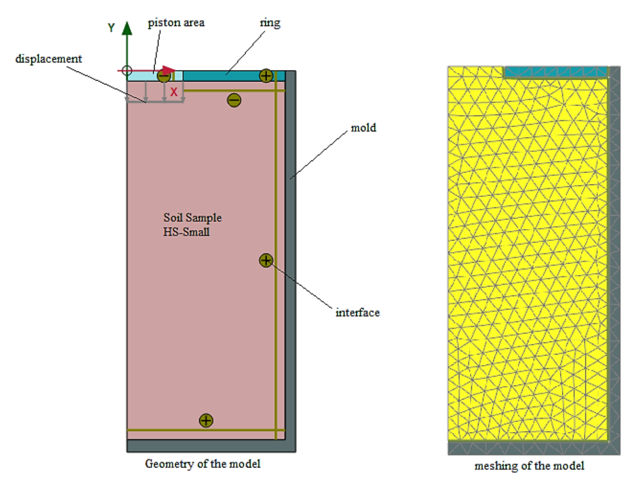

Figure 3. Numerical Model CBR test.
Source: Authors.

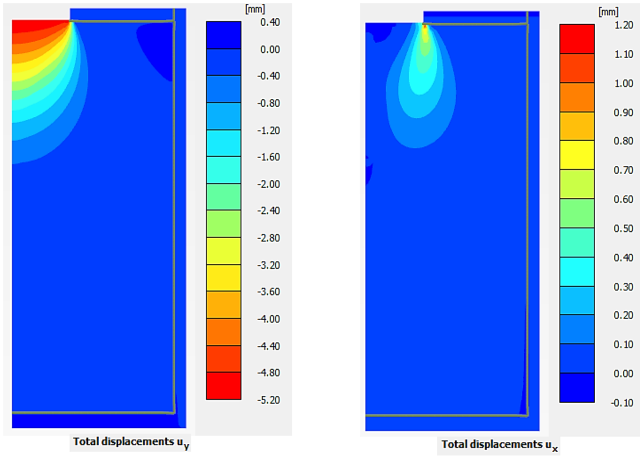

Figure 4. Typical displacement distribution at final stages (5.08 mm piston penetration).
Source: Authors.

diameter of depth. Horizontal displacement is highly concentrated at the piston border. Horizontal-displacement bulb penetration reaches up to one piston diameter of depth. For the five samples, the numerical simulation shows a rigid triangle-shaped zone under the piston in which the soil moves almost exclusively downward. This behavior is common in bearing capacity phenomena.

Some debate has focused on whether CBR is similar to a bearing test or whether it can be correlated to a stress-strain test. The authors consider that simple constitutive models may not contribute to this type of dilemma. Therefore, some considerations can be pointed out in this regard since this research uses a constitutive equation that considers small strain and the degradation of moduli. It can be inferred in Fig. 5 that CBR tests involve a strong degradation of moduli. Critical softening in almost the entire sample occurs at 5.08 mm of piston penetration, but not at 2.54 mm which is usually the penetration level for the CBR value. It can be noted that, although at 2.54 mm the stiffness of the sample has not completely degraded, most of it has undergone some softening.

The comparison between the rate of degradation of the stiffness and the mobilization of the shear stress shows that both parameters strongly interfere with CBR response. Fig. 6 shows the typical spatial distribution of the shear ratio, i.e. the ratio between the mobilized shear stress and maximum shear, at different piston penetration levels during the simulated CBR test. The strength limit state, which occurs when mobilized shear equals available maximum shear stress, covers a small area of the sample. Furthermore, it is clear that the maximum values of shear stress are localized near the end of the piston during the entire test. At 2.54 mm of penetration, which is a typical CBR value, the vast majority of the sample exhibits relatively low shear stress ratio saturations. On the contrary, complete stiffness degradation covers more than half of the sample at the same level of penetration. These findings seem to suggest that in the case of the HS-Small constitutive model, the strength and stiffness parameters are strongly correlated to the response to CBR.

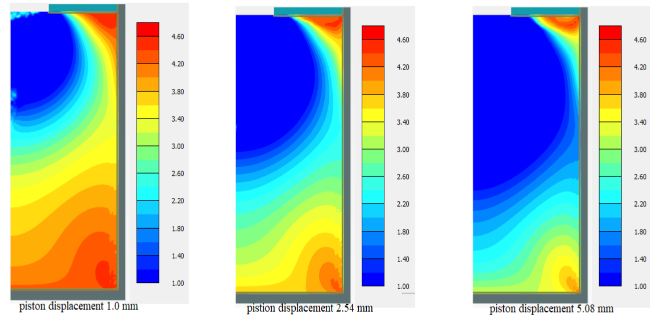

Figure 5. Typical stiffness ratio G/Gur distribution at different levels of penetration.
Source: Authors.

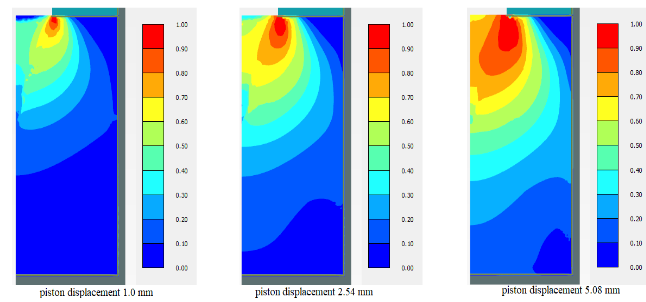

Figure 6. Typical shear ratio τ_{mob}/τ_{max} distribution at different levels of penetration.
Source: Authors.

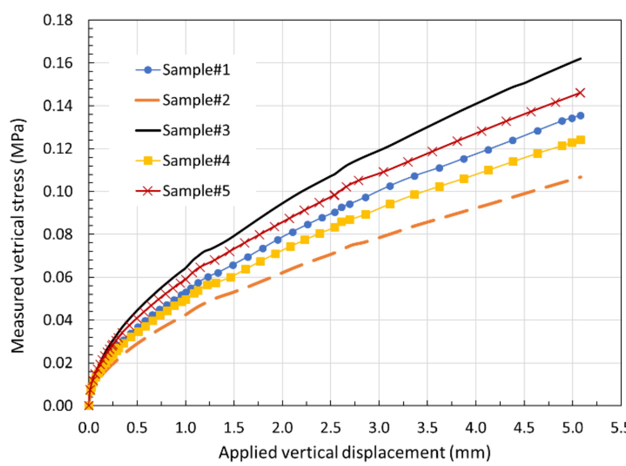

Figure 7. Numerical simulation results of the CBR test.
Source: Authors.

Finally, to fulfill the purpose of this study, Fig. 7 shows the CBR curves of the five synthetic soil samples whose geotechnical parameters were determined using previously presented criteria and correlations extracted from recent literature. The curves of the simulated CBR tests are not contrasted against tests executed on real samples. Instead, only the CBR values are compared with a reference or typical values for soils in the city of Bogotá. The maximum CBR values were found at a penetration of 2.54 mm. For each of the samples, the CBR value is presented in Table 6.

Table 6.
CBR results using HS-Small model (at 2.54 mm).

Sample	Vertical Stress MPa	CBR %
#1	0.197	1.31
#2	0.152	1.04
#3	0.160	1.57
#4	0.121	1.21
#5	0.142	1.42

Source: Authors.

Table 7.
Identification of samples for parametric study.

ID	Description
AF	Corresponds to sample with friction angle decreased by 10 % and recalculating the coefficients of earth pressures; remained parameters keeps the same value.
BF	Corresponds to sample with friction angle increased by 10 % and recalculating the coefficients of earth pressures; remained parameters keeps the same value.
AG	Sample with E_{edo}, E_{ur}, E_s, G_0 parameters decreased by 10 %, but keep all other parameters the same.
BG	Sample with E_{edo}, E_{ur}, E_s, G_0 parameters increased by 10 %, but keep all other parameters the same.

Source: Authors.

Considering that the HS-Small parameters of the samples used in the simulations were obtained from average index values, typical of the Sabana Formation, it is remarkable that the numerical result of the CBR will yield typical average values of the field tests consulted in the literature.

Finally, a parametric analysis for stiffness and resistance parameters is presented here to find their incidence on the CBR numerical tests. For this purpose, additional simulations were carried out with four variations of the original samples. The variations consisted of decreasing and increasing the friction angle by 10 % and decreasing or increasing the stiffness parameters by 10 %. In all cases, the overconsolidation and cohesion (and cut off) remained constant.

Type A samples consist of a 10 % decrease in the respective parameter, while type B samples correspond to an increase of said parameter by 10 %. The letters F and G correspond to the adjusted parameter: friction angle letter F, and stiffness modulus letter G. The following table summarizes the description.

Thus, from the original samples Sample 1 to Sample 5, twenty additional samples were made adjusting the resistance or rigidity parameters as described above. Table 7 presents the adjusted parameters involve in the parametric study. When a parameter keeps the same value of the original sample Table 7 calls the character # and the number of the original sample.

For the sake of brevity, Fig. 8 presents the results of the parametric analysis of the CBR test modeling by varying the stiffness or resistance parameters for sample #2. The load displacement curvature is typical of the nonlinear elastoplastic constitutive model. In Fig. 8 it can also be verified that the stiffness parameters have a greater incidence than the resistance parameters.

Table 8.
Values of parameters for parametric study.

No.	ϕ' °	E_{edo} N/mm^2	E_{ur} N/mm^2	G_0 N/mm^2	$K_{0\,SC}$	$K_{0\,NC}$
#1	**31.94**	**1.6**	**8.3331**	**13.463**	**0.987**	**0.422**
#1AF	28.746	#1	#1	#1	1.017	0.47
#1BF	35.134	#1	#1	#1	0.946	0.375
#1AG	#1	1.44	7.4998	12.1167	#1	#1
#1BG	#1	1.76	9.1664	14.8093	#1	#1
#2	**29.7**	**1.095**	**6.0035**	**10.0056**	**1.009**	**0.455**
#2AF	26.73	#2	#2	#2	1.032	0.5
#2BF	32.67	#2	#2	#2	0.978	0.41
#2AG	#2	0.9855	5.4031	9.005	#2	#2
#2BG	#2	1.2045	6.6038	11.0061	#2	#2
#3BF	30.206	#3	#3	#3	1.101	0.447
#3AF	24.714	#3	#3	#3	1.125	0.532
#3	**27.46**	**1.934**	**8.8221**	**15.086**	**1.117**	**0.489**
#3AG	#3	1.7406	7.9399	13.5774	#3	#3
#3BG	#3	2.1274	9.7043	16.5946	#3	#3
#4BF	31.438	#4	#4	#4	0.883	0.428
#4AF	25.722	#4	#4	#4	0.942	0.516
#4	**28.58**	**1.705**	**8.1369**	**13.7494**	**0.915**	**0.472**
#4AG	#4	1.5345	7.3232	12.3744	#4	#4
#4BG	#4	1.8755	8.9505	15.1243	#4	#4
#5BG	#5	2.1615	10.2957	17.3973	#5	#5
#5AG	#5	1.7685	8.4238	14.2342	#5	#5
#5BF	31.438	#5	#5	#5	0.992	0.428
#5AF	25.722	#5	#5	#5	1.038	0.516
#5	**28.58**	**1.965**	**9.3598**	**15.8158**	**1.019**	**0.4716**

Source: Authors.

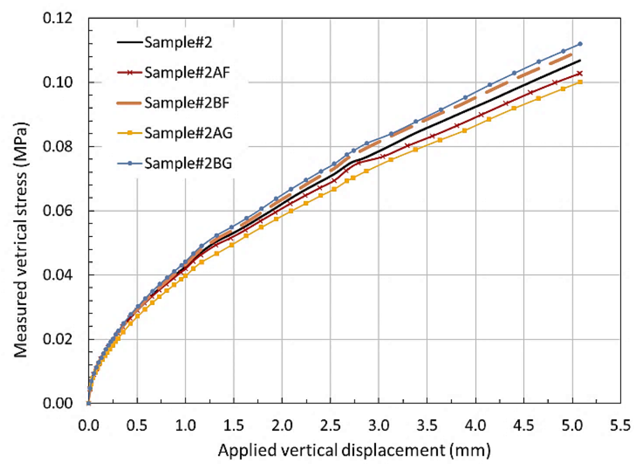

Figure 8. Numerical simulation results of the CBR for sample#2 – parametric study.
Source: Authors.

Table 9 presents the CBR results of the modeling and the variations with respect to the reference sample. Through parametric analysis It was evidenced that both the resistance parameters (and initial stress state - K0) and the stiffness parameters (G degradation curve) have an impact on the CBR result. For the samples with high friction angle and high overconsolidation ratio, the variation of the resistance parameters was not proportional. For sample#1 the symmetric variation +/-10 % of the friction angle produced an asymmetric response of CBR (-1 % and +5 %), while for sample #3 the variations produced an always positive

Table 9.
Results of CBR - parametric study.

Sample	CBR %	Variation
#1	1.31	--
#1AF	1.30	-1.09 %
#1BF	1.38	5.29 %
#1AG	1.26	-4.25 %
#1BG	1.43	8.81 %
#2	1.04	--
#2AF	1.01	-2.75 %
#2BF	1.06	2.49 %
#2AG	0.97	-6.54 %
#2BG	1.08	4.49 %
#3	1.56	--
#3AF	1.62	3.57 %
#3BF	1.74	11.03 %
#3AG	1.60	2.40 %
#3BG	1.65	5.34 %
#4	1.21	--
#4AF	1.17	-3.26 %
#4BF	1.24	2.41 %
#4AG	1.13	-6.48 %
#4BG	1.28	6.14 %
#5	1.42	--
#5AF	1.38	-3.37 %
#5BF	1.47	3.01 %
#5AG	1.35	-5.24 %
#5BG	1.49	4.71 %

Source: Authors.

variation in the CBR. For samples #2, #4 and #5, which coincide with the lowest friction angles and overconsolidation ratios the responses were proportional. For these samples, it was found that varying the friction angle by 10 % causes a variation that does not exceed 3.3 % of the CBR value of the reference samples, while raising or lowering the modulus degradation curve vertically in a ratio of 10 % causes sensitive variations in the CBR result, with ratios of change ranging between 2.4 and 6.5 % compared to the reference samples.

6 Conclusion

Different criteria and correlations have been developed in recent years for the largest soil deposit in the city of Bogotá. These criteria and correlations can be used to estimate the set of resistance and stiffness parameters of the HS-Small constitutive model with appropriate precision. This paper shows how to perform this characterization from index properties and others considerations.

A set of five synthetic samples was elaborated based on typical index properties of Bogotá soil. The soils are representative of the most superficial part by assigning high OCR values. However, the same set of parameters could represent soils at other depths by adjusting this ratio.

To show reliability, numerical CBR tests were performed in drained conditions. Although an inspection of the curves does not exactly match that of tests with samples from the site, the numerical CBR values at 2.54 mm are in the midrange of the typical values for soils in the City.

Additionally, a short discussion is presented on the applicability of the CBR as a test to determine the deformation properties of soils. Simulations show that the HS-Small constitutive model could contribute to this discussion by showing that even at low piston displacements, the degradation of the stiffness modulus occurs in a large part of the sample.

This work confirms that the set of parameters of the HS-Small model of the city of Bogotá can be determined with high accuracy from quick and inexpensive tests. Therefore, it contributes to the implementation of complex numerical analyzes for specific urban projects, even in early instances, when mechanical tests are not available.

The HS small constitutive model allows obtaining CBR values by simulating controlled displacement tests under axisymmetric conditions. In the present study it was possible to verify that, for dry tests, of over-consolidated soils with low cohesion, variations in the friction angle lead to slight variations in the CBR result. In contrast, variations in the stiffness parameters cause significant variations in the final result of the simulated CBR.

It can be inferred that the HS Small constitutive model, by incorporating a shear modulus degradation curve, generates a response in the CBR model that is more correlated with material stiffness than with friction angle, which may imply that the test of CBR if it would be correlated with the resilient modulus of the soil rather than with the resistance parameters.

In this study, the drained cohesion c' intercept is estimated from undrained shear strength S_u as suggested in eq. (13) and making ξ=5.

$$c' = \frac{1}{\xi}(S_u)OCR^{sin\phi} \tag{13}$$

This expression follows recommendation from Norwegian Geotechnical Institute – NGI – and involves the fact that drained cohesion appears on overconsolidated soils, so it is related to overconsolitation ratio - OCR.

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