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Bearing capacity of footings in unsaturated soils employing analytic methods

Obtención de la capacidad de carga en cimentaciones para un suelo parcialmente saturado empleando métodos analíticos

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Abstract

The study of the behavior of unsaturated soils has been the subject of several studies in recent years. The objective of this paper is to summarize the main aspects and different theories established by reference authors, used to estimate bearing capacity of unsaturated soils. The variation in the bearing capacity of a square shaped foundation surface: sides B = L 1.5 m is obtained, using the approach proposed by Brinch-Hansen considering the formulations offered by Fredlund and Vanapalli to estimate the unsaturated soil strength parameters (c and φ). Each of the reviewed formulations suggests a law of variation of cohesion values depending on the unsaturated suction function. A comparison of the behavior between the unsaturated and the saturated phases, is performed, using different values of matric suction obtained by means of the soil retention curve of Formation Capdevila.

Keywords: bearing capacity, suction, the soil-water characteristic curve, unsaturated soils.

Resumen

El estudio del comportamiento de los suelos parcialmente saturados ha sido motivo de diversos estudios en los últimos años. La presente investigación se encarga de resumir los principales aspectos y diferentes teorías enunciadas por varios autores para estimar capacidad de carga de los suelos parcialmente saturados. Se obtiene la variación de la capacidad de carga de una cimentación superficial cuadrada de lado B y L de 1.5 m, empleándose la formulación propuesta por Brinch-Hansen, y tomando en consideración las formulaciones propuestas por Fredlund y Vanapalli, para estimar los parámetros de resistencia del suelo parcialmente saturado (c y φ). Estas formulaciones proponen una ley de variación de los valores de cohesión de un suelo parcialmente saturado en función de la succión que este pueda experimentar. Se realiza la comparación entre el comportamiento en la fase saturada y la fase parcialmente saturada, empleando diferentes valores de succión matricial obtenidos por medio de la curva de retención del suelo de la Formación Capdevila.

Palabras claves: capacidad de carga, curva de retención, succión, suelos parcialmente saturados.

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I. INTRODUCTION

The study of the geotechnical behavior of soils has been developed considering the soils are saturated or unsaturated. However, there are important geotechnical problems where the study of unsaturation is essential, since much of the geological formations in the world, are mostly unsaturated soils. [1]–[3].

The bearing capacity of soil is associated to ability to support different types of tension due to the presence of loads imposed by the superstructure and its maximum value is related to the maximum stress registered, before the failure occurs by shear or loss of stability. This value varies depending on the type of soil being treated, as well as the magnitude and distribution of loads acting on the foundation.

The hypothesis of this research states that the bearing capacity of the shallow foundation, placed on an unsaturated soil from the Capdevila formation, increases when considering the suction effect.

II. THEORETICAL FRAMEWORK AND METHODOLOGY

A. Bearing capacity of unsaturated soils

The bearing capacity of shallow foundations is estimated using approaches originally presented by Terzaghi and Meyerhof assuming that the soil is saturated, [4]. The shallow foundations are placed above the water level and the variation of tensions with respect to depth, associated with how the loads of the superstructure are distributed through the substructure (shallow foundations), in unsaturated soils. The bearing capacity of a shallow foundation depends mostly on the foundation´s width, additionally this study results show that the capacity of these soils (for the same width) is significantly influenced by the suction values.

Fredlund in 1993 suggested that the strength parameters for unsaturated soils affected by the influence of suction can be obtained from the strength parameters of the saturated soil, equation 1 and 2. [1]

$$c_{unsat} = c_{sat}{}' + (u_a - u_w)\, tan\, \phi^b \qquad (1)$$

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$$\phi_{unsat} = \phi_{sat} \qquad (2)$$

Where $c_{sat}{}'$ is the effective cohesion, $(u_a - u_w)$ is the matric suction $\phi_{sat}{}'$ is the effective angle of internal friction and ϕ^b is the slope angle of the failure envelope with respect to matric suction, when $\phi^b < \phi_{sat}$.

Moreover, Fredlund suggests that there is a relationship between the $\phi^b <$ ϕ_{sat} and given by: (Equation 3)

$$\chi = \frac{Tan\ \phi^b}{Tan\ \phi_{sat}} \qquad (3)$$

If assumed as valid that $x = S_r$ proposed by Beneyto [5] and Alanís [6], then: (Equation 4)

$$\phi^b = arctan\left(S_r\ Tan\ \phi_{sat}\right) \qquad (4)$$

Replacing strength parameters, C_{Fredlund} and ϕ_{Fredlund} in Brinch-Hansen formula. (Equation 5)

$$q_u = \left[c_{sat}{}' + (u_a - u_w)\ tan\ \phi^b\right] N_c S_c i_c d_c g_c + \gamma d N_q S_q i_q d_q g_q + 0.5\gamma B N_\gamma S_\gamma i_\gamma d_\gamma g_\gamma \qquad (5)$$

Where $c_{sat}{}'$ is the effective cohesion, γ is the specific weight, D_f is the footing base level, B is the footing width, $(u_a - u_w)$ is the matric suction, $\phi_{sat}{}'$ is the effective angle of internal friction, ϕ^b is the slope angle of the failure envelope with respect to matric suction, S_γ, S_q, S_c are shape factors of Brinch-Hansen, i_c, i_q, i_γ, are load slope factors of Brinch-Hansen, d_γ, d_q, d_c are depth factors of Brinch-Hansen, g_c, g_q, g_γ are sloped terrain factors of Brinch-Hansen, and N_γ, N_q, N_c are bearing capacity factors of Brinch-Hansen.

Vanapalli and Mohamed suggest the semi-empirical equation based on the model of surface balance tests for predicting the variation of bearing capacity with respect to the matric suction in unsaturated soils as follows. [7], [8]. (Equation 6)

$$\begin{aligned} q_u = \Big[c_{sat}{}' &+ (u_a - u_w)_b\left(tan\ \phi_{sat}{}' - S_r{}^{\psi} tan\ \phi_{sat}{}'\right) \\ &+ (u_a - u_w)_{AVR}\, S_r{}^{\psi} tan\ \phi_{sat}{}'\Big] N_c S_c d_c + \gamma D_f N_q S_q d_q + 0.5\gamma B N_\gamma S_\gamma d_\gamma \end{aligned} \qquad (6)$$

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Where c_{sat}' is the effective cohesion, γ is the unit specific weight, D_f is the footing base level, B is the footing width, $(u_a\text{-}u_w)_b$ is the air-entry value from the soil-water characteristic curve, $(u_a\text{-}u_w)_{AVR}$ average air-entry value, ϕ_{sat}' is the effective angle of internal friction, S_r is the degree of saturation, ψ is a fitting parameter, S_γ, S_q, S_c are shape factors of Vesic, d_γ, d_q, d_c are depth factors and N_γ, N_q, N_c are bearing capacity factors of Vesic.

Performing an adjustment of the equation proposed by Brinch - Hansen, which is used by the Cuban Normative (NC 2007), with unsaturated soil parameters that refer to [10]. After replacing the values, as follows for unsaturated soils. (Equations 7, 8 and 9)

$$q_u = \left[c' + (u_a - u_w)_b\left(tan\phi_{sat} - S_r^{\Psi} tan\phi_{sat}\right) + (u_a - u_w)_{AVR} S_r^{\Psi} tan\phi_{sat}\right] N_c S_c i_c d_c g_c + \gamma d N_q S_q i_q d_q g_q + 0.5\gamma B N_\gamma S_\gamma i_\gamma d_\gamma g_\gamma \quad (7)$$

$$\Psi = 1.0 + 0.34\,(PI) - 0.0031\,(PI^2) \quad (8), [8]\text{-}[9]$$

$$\phi_{unsat} = \phi_{sat} + \psi_d \quad (9)$$

Where c_{sat}' is effective cohesion, γ is the unit specific weight, D_f is the footing base level, B is the footing width, $(u_a\text{-}u_w)_b$ is the air-entry value from the soil-water characteristic curve, $(u_a\text{-}u_w)_{AVR}$ average air-entry value, ϕ_{sat}' is the effective angle of internal friction, S_r is the degree of saturation, ψ is a fitting parameter, S_γ, S_q, S_c are shape factors of Brinch-Hansen, i_c, i_q, i_γ are load slope factors of Brinch-Hansen, d_γ, d_q, d_c are depth factors of Brinch-Hansen, g_c, g_q, g_γ are sloped terrain factors of Brinch-Hansen and N_γ, N_q, N_c are bearing capacity factors of Brinch-Hansen. The parameter Ψ depends on soil plasticity index (PI), this adjustment parameter is obtained by Equation 8.

Dilatancy has a significant influence on the volumetric response of granular soils, is a volume change when shear stresses, applied Figure 1. [11]

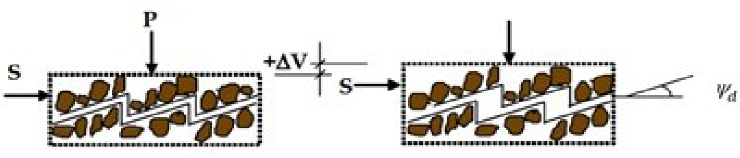

Figure 1. The dilatancy model in granular soils. [11]

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Dilatancy for direct shear test can be obtained by expression 10. [11]

$$\frac{S}{P} + \frac{dy}{dx} = \psi_d \quad (10)$$

Where S is the tangential stress, P is the normal stress, d_y is the displacement in the y-axis, d_x is the displacement in the x-axis and ψ_d is degree of dilatancy (°).

The degree of dilatancy values are controversial and have great influence on the geotechnical behavior of shallow foundations, [12], [13]; the absence of a single criterion Haramboure [14] considered null ($\psi_d = 0^o$) in all frictional soils, this being a conservative approach from the proposal Bolton [12] for frictional soils $\phi \leq 30°$ and which can be estimated considering that $\psi_d = \phi - 30°$for soils with $\phi > 30°$.

Mohamed and Vanapalli assume that the dilatancy value will be 10% of the angle of internal friction of the soil, [7]. This approach is the chosen for the further analysis of soils in this paper.

III. RESULTS AND DISCUSSION

A. Soil characterization - Capdevila

To carry out the tests on the soil for the study and classification, current Cuban Normative NC and ASTM indications were followed: determination of the particle size, specific gravity, liquid limit, plastic limit and plasticity index, standard Proctor, suction and direct shear test. The results of physical and mechanical tests performed on soil samples studied below. [16]

- ***Particle size distribution, consistency limit, specific gravity and compaction test***

Determination of particle size, specific gravity, liquid limit, plastic limit and plasticity index, Proctor Standard: To carry out the tests in soils under study and classification guidelines to currently existing ASTM normative were followed and suction in soils. The results of physical tests performed on soil samples are shown below in the Table 1.

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Proctor Standard test was performed to Capdevila soil samples, necessary to obtain the values of maximum dry unit weight and optimum moisture to have a reference when working on remolded samples because there could not be obtained undisturbed samples. The remolding of the sample used in the research was done following the method of using 90% of the maximum dry unit weight as a fixed parameter, always working on the dry branch of the Proctor Standard curve. This test was performed taking into account the standard. (Table 1)

Table 1. Experimental results of the soil Capdevila

Parameters	Units	Capdevila
Gravel	(%)	2.48
Sand	(%)	20.89
Silt and Clay	(%)	76.63
Limited Liquid (LL)	(%)	52
Limited Plastic (LP)	(%)	21
Plasticity Index (PI)	(%)	31
Relative specific weight of the solid particles (Gs)	(-)	2.72
Specific weight dry ()	(kN/m3)	14.8
Optimum moisture ()	(%)	23

Depending on the results of the particle size and consistency limit soil studied, the soil is classified as CH (clay high compressibility).

- ***The soil-water characteristic curve of the soil studied***

To determine soil suction, it was taken as the ASTM standard for obtaining suction in the laboratory (ASTM: D 5298, 2010), experimental results suctions of the soil samples used in the research are presented below in Figure 2. The suction test was performed using Whatman filter paper 42.

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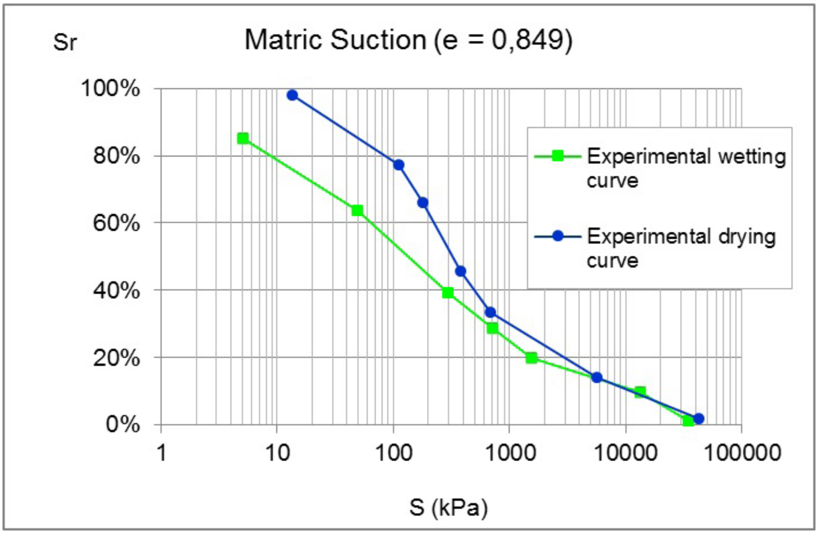

Figure 2. The experimental soil-water characteristics curves of Capdevila for compacted soils. (e = 0.849). [15]

Resistance parameters of saturated soil studied

This test is performed in order to determine the parameters of soil strength (ϕ - c), considering the standard (NC-325 2004.) Corresponding to Geotechnical Determination of direct shear resistance (box apparatus small cut). To carry out this test, specimens compacted with the energy of Standard Proctor were used. Each of the samples was applied to a vertical load of 50, 100 and 200 kPa, with an application rate of 0.4 mm/min on Capdevila soil.

As a result, stress values of the soil samples tested were gathered. It is shown in Figure 3 the curve of σ vs $\tau_{máx}$.

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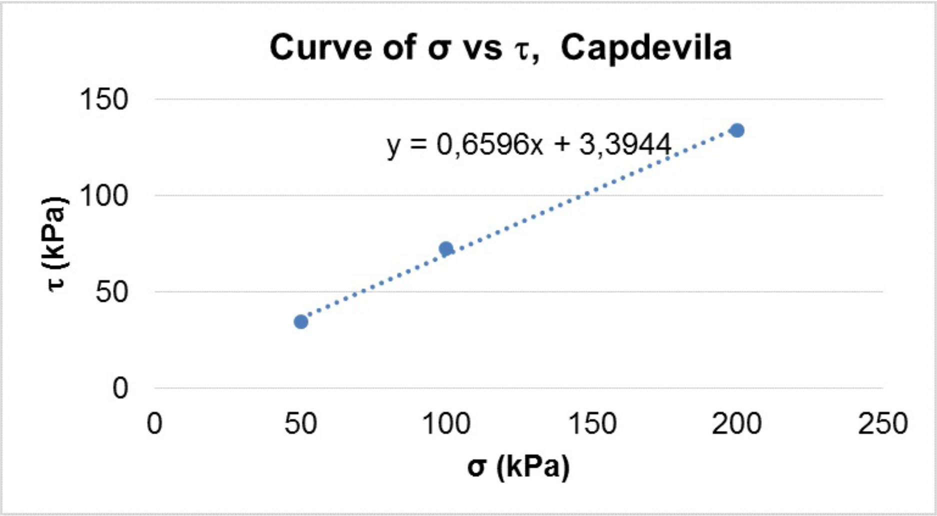

Figure 3. Curve of σ vs $\tau_{máx}$ soil Capdevila formation.

As a result, the graph parameters for Capdevila soil resistance, Table 2. The test was performed with samples of saturated soils, through the flooding of cutting box.

Table 2. Parameters strength of soils objects of study.

Parameters	Capdevila
Cohesion C, (kPa)	3.4
Effective angle of internal friction ϕ, (°)	33.4

The sampling was preformed based on a random procedure at the geological site of the Capdevila Formation. The samples where extracted undisturbed, following the corresponding normative. After performing 5 cycles of laboratory tests, average values of properties and parameters were determined for each soil studied.

Results of the capacity of the soil - Capdevila

In Cuba, the soils do not experience saturation values below the 60%, so obtaining the bearing capacity and predict the foundation´s settlement on unsaturated soils, it is valid for suctions between 0 - 200 kPa.

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This case study research foundation is a square surface side B and L 1.5 m, with foundation depth of 1.5 m and the total base height 0.45 m; the pedestal section 0.3 m x 0.3 m and a height of 1.05 m. The foundation will be supported on the ground from Capdevila Formation, where the bearing capacity is determined when the degree of saturation variations occur. (Figure 4)

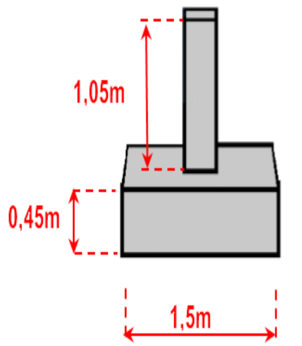

Figure 4. Geometrical characteristics of the foundation used in the case study.

To analyze the bearing capacity of the foundation described above, the characteristics shown in Table 3 were taken as initial data. The results of the properties of soil bearing capacity Capdevila using formulation Brinch-Hansen (NC 2007), soil c - ϕ modified ($C_{Vanapalli}$ and $\phi_{Vanapalli}$) and ($C_{Fredlund}$ and $\phi_{Fredlund}$), under the influence of suction, (equation 5 and 7), are reflected in Table 4, Table 5 and Figure 5.

Table 3. Data of foundation and soil Capdevila

Foundation			Soil - Capdevila				
B (m)	L (m)	Df (m)	ϕ_{sat} (°)	ψ_d (°)	C_{sat} (kPa)	PI (%)	$(u_a - u_w)_b$ (kPa)
1.5	1.5	1.5	33.4	3.34	3.4	30.6	120

- ***Analytical Methods (Vanapalli and Fredlund)***

The results of calculating the bearing capacity of the soil formation Capdevila, the void ratio (e = 0.842) using the formulation Brinch-Hansen of modified ($C_{Vanapalli}$ and $\phi_{Vanapalli}$) and ($C_{Fredlund}$ and $\phi_{Fredlund}$) is varying the values of suction.

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Table 4. Ultimate bearing capacity of the soil - Capdevila, variable suction ($C_{Vanapalli}$ and $\phi_{Vanapalli}$)

Brinch-Hansen (e=0.842) (Equation 7, 8 and 9)															qu (kPa) B-H Vanapalli
Soil- Capdevila						Bearing capacity factors			Shape factors			Depth factors			
$(u_a - u_w)_{AVR}$ (kPa)	S_r (%)	γ* (kN/m³)	q* (kPa)	$\phi^*_{uv\sigma}$ (°)	C^*_{uns} (kPa)	N_γ***	N_q	N_c	S_γ	S_q	S_c	d_γ	d_q	d_c	q_u (kPa) B-H Vanapalli
0	100	18.1	27.1	31.88	2.34	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	1364.10
50	100	18.1	27.1	31.88	23.79	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	2608.41
100	98	18.0	27.0	31.88	46.60	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	3924.82
150	91	17.7	26.6	31.88	59.60	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	4659.42
200	84	17.4	26.1	31.88	61.62	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	4757.28

Table 5. Ultimate bearing capacity of the soil - Capdevila, variable suction ($C_{Fredlund}$ y $\phi_{Fredlund}$)

Brinch-Hansen (e=0.842) (Equation 5)															
Soil- Capdevila						Bearing capacity factors			Shape factors			Depth factors			qu (kPa) B-H Vanapalli
$(u_a - u_w)_{AVR}$ (kPa)	S_r (%)	γ* (kN/m³)	q* (kPa)	$\phi^*_{uv\sigma}$ (°)	C^*_{uns} (kPa)	N_γ	N_q	N_c	S_γ	S_q	S_c	d_γ	d_q	d_c	
0	100	18.1	27.1	31.88	2.34	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	1364.10
50	100	18.1	27.1	31.88	25.08	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	2683.08
100	98	18.0	27.0	31.88	46.91	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	3942.83
150	91	17.7	26.6	31.88	64.42	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	4939.05
200	84	17.4	26.1	31.88	78.74	27.2	22.86	35.15	0.6	1.62	1.65	1	1	1	5750.61

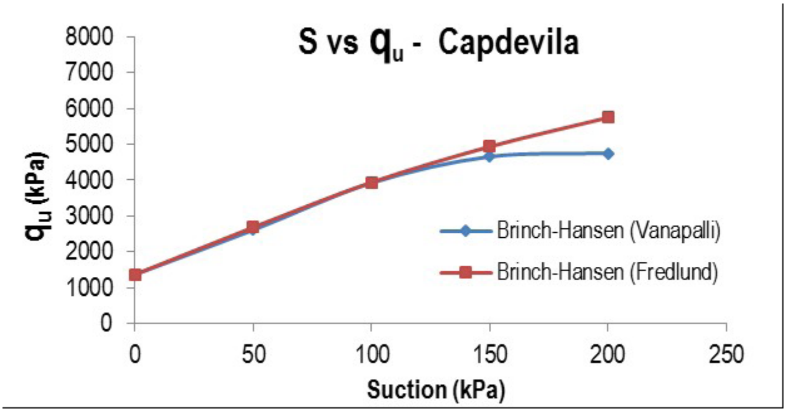

Figure 5. Curve of ultimate bearing capacity vs suction for formulating Brinch-Hansen modified of ($C_{Vanapalli}$ and $\varphi_{Vanapalli}$) and ($C_{Fredlund}$ and $\varphi_{Fredlund}$), soil - Capdevila.

In obtaining the bearing capacity of a shallow foundation resting on a unsaturated soil, the formulation that best describes the behavior of the soil is raised suggested by Brinch-Hansen modified ($C_{Vanapalli}$ and $\phi_{Vanapalli}$), which takes into consideration soil characteristics by using suction, the degree of saturation, the plasticity index; and wherein a value for the suction capacity begins to decrease becoming asymptotic as the soil becomes drier; being different in the case of the formulation proposed by Brinch-Hansen modified ($C_{Vanapalli}$ and $\phi_{Vanapalli}$) where the value of carrying capacity of unsaturated soil increases indefinitely as matric suction increases.

The unsaturated soil Capdevila Formation modifying cohesion by employing the formulation of Vanapalli, the bearing capacity starts to decrease for a given value of suction depending of the soil type, showing a rearrangement of particles with a decreased volume when a decrease in the degree of saturation occurs. (Figure 5)

IV. CONCLUSIONS

The study of unsaturated soil treatment requires effort of new variables, such as suction, which can significantly affect their behavior.

The load capacity in unsaturated soils friction increases from 2 to 4 times as compared to the saturated condition, with increasing suction on the floor, due to a decrease in the degree of saturation.

The method that best describes the behavior of unsaturated soil from Capdevila Formation is suggested by Vanapalli for modifying the strength parameters of the soil, where it takes into account in its formulation, soil characteristics by using suction, the degree of saturation and soil plasticity index. Unlike the Fredlund's formulation raised by the value of carrying capacity increases as soil matric suction increases indefinitely, for developing this capacity value, Vanapalli load starts to decrease for a particular suction value, which is a function of soil type that evidenced a rearrangement of the particles it occurs when a decrease in the degree of saturation.

For soils with a high value in the angle of internal friction, such as soil of Capdevila Formation, which has a ϕ = 33.4 °, the capacity begins to decrease from a value of suction depending on the soil characteristics. In this case, for values above 150 kPa, Table 5.

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REFERENCES

[1] D. G. Fredlund and H. Rahardjo, *Soil Mechanics for Unsaturated Soils*. I. JOHN WILEY & SONS. Wiley-Interscience., University of Saskatchewan: A, 1993. DOI: 10.1002/9780470172759

[2] D. G. Fredlund, "Relevance of Unsaturated Soil Mechanics in Geotechnica Engineering," *Conf. in Havanna.*, 2002.

[3] M. Barrera and P. Garnica, *Introducción a la mecánica de suelos no saturados en vías terrestres*, Publicación., no. 198. Sanfandila, Querétaro: Secretaría de Comunicaciones y Transporte, Instituto mexicano del transporte, 2002, pp. 1–155. ISSN 0188-729. Disponible en web: www.imt.mx/archivos/Publicaciones/PublicacionTecnica/pt198.pdf

[4] B. M. Das, *Fundamentos de Ingeniería Geotécnica*, 7ma edición. Sacramento, California State University: THOMPSON LEARNING, 2011, pp. 1–880.

[5] P. A. Beneyto, "Análisis de consolidación en suelos regionales en estado de saturación parcial mediante simulación numérica utilizando el método de los elementos finitos." Tesis de Maestría, Departamento de Mecánica Aplicada, Facultad de Ingeniería, Universidad Nacional del Nordeste, 2003. Disponible en web: http://ing.unne.edu.ar/mecap/Investigacion/Tesis/MgBeneyto-Res.pdf

[6] A. Alanís, "Deformación volumétrica en suelos no saturados", Tesis de Maestría, Universidad Autónoma de Querétaro. México, 2012. Disponible en web: http://hdl.handle.net/123456789/2317.

[7] F. M. O. Mohamed, S. K. Vanapalli, and M. Saatcioglu, "Bearing capacity and settlement behaviour of footings in an unsaturated sand," in *14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering*, Vol. October 2, 2011, pp. 1–8.

[8] W. T. Oh and S. K. Vanapalli, "Bearing capacity of low plastic unsaturated soils using effective and total stress approaches," in *14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering.*, 2011, pp. 1–8.

[9] J. G. Tristá, "Estudio del comportamiento tenso-deformacional de suelos parcialmente saturados en Cuba," Tesis de Doctorado, Instituto Superior Politécnico "José Antonio Echeverría," 2015.

[10] S. K. Vanapalli and W. T. Oh, "A model for predicting the modulus of elasticity of unsaturated soils using the soil-water characteristic curve," *Int. J. Geotech. Eng.*, vol. 4, pp. 425–433, 2010. DOI: 10.3328/IJGE.2010.04.04.425-433

[11] C. García, "Determinación experimental de la función de dilatancia de suelo granular denso.," *Geogaceta*, 1995. ISSN: 0123683 X.

[12] M. D. Bolton, "The strength and dilatancy of sands," *Geotechnique*, vol. 26, no. 1, pp. 65–78, 1986. ISSN 0016-8505. DOI:10.1680/geot.1986.36.1.65

[13] A. V. Gonzalez–Cueto, E. González, and G. Quevedo Sotolongo, "Asentamientos, Aplicación de Métodos Analíticos y Numéricos en el cálculo de cimentaciones superficiales en suelos friccionales," in *10mo Simposio Internacional de Estructuras, Geotecnia y Materiales de Construcción.*, 2013. ISBN: 959-250-024-x

[14] Y. Haramboure, "Influencia de la directriz de un cimiento laminar de revolución ene el estado tenso-deformacional de suelo. Caso de estudio: Depósito elevados tipo Güira," Tesis de Doctorado, Instituto Superior Politécnico "José Antonio Echeverría," 2014.

[15] J. Guardo, "Estudios Geotécnicos. Una necesidad en obras civiles," *Rev. Ing. y Desarro. Univ. del Norte*, vol. 6, pp. 117–126, 1999. ISSN: 2145-9371 Disponible en web: http://cientificas.uninorte.edu.co/index.php/ingenieria/article/viewFile/2228/1445

[16] J. Tristá, W. Cobelo, G. Quevedo, and C. García, "Comportamiento volumétrico de un suelo de la formación Capdevila en condiciones de saturación parcial," *Rev. Cuba. Ing.*, vol. VI, no. 2, pp. 5–15, 2015. ISSN 2223 -1781. DOI: 10.1139/cgj-2013-0332 . Disponible en web: http://rci.cujae.edu.cu/index.php/rci/issue/view/19/showToc