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Comparing Geotechnical Methods to Assess Primary Consolidation Settlements for Raft Foundations

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Abstract: The primary consolidation settlements in soils under pressure due to raft foundations were evaluated using the Excel DISBAL book, and the results of the classical procedure for calculating primary settlements, taking into account the soil compression index, were compared with those of the simplified procedure based on the summation of layers method, recommended by the current Cuban standard of surface foundations. The novelty of Excel DISBAL book is its contribution for solving shortcomings of software based on current geotechnical methods and in accordance with the legal framework of current construction regulations in Cuba and other international references. The case study deals with the evaluation of the extension in height of a building supported in soil deformation limit state and hypothetically located in the experimental field of Civil Engineering of Universidad de Oriente, where the coves were made by the National Research Company Applied from Santiago de Cuba. It is demonstrated that this software allows an adequate assessment of the limit state due to soil deformation by both methods, obtaining acceptable primary consolidation settlements for the case study, and helping to specify the number of floors the building will reach.

Key words: primary consolidation; settlements; raft foundation; geotechnical design; Excel workbook DISBAL

1. Introduction

The geotechnical design of the foundation takes into account the ultimate limit state of the foundation, building overturning, foundation sliding and service limit states, such as settlement, to ensure that the maximum absolute settlements or allowable differences are not exceeded.

Theoretical and empirical research is currently being carried out to evaluate the calculation methods for the geotechnical design of foundations (Chagoyén and Negrín 2009). There are many methods for the calculation of primary settlement based on linear models of soil behaviour (Oh and Vanapalli 2011), such as the sum-of-layers method recommended by the Cuban standard for geotechnical design of shallow foundations (2007).

The assessment of primary settlement is often performed by methods that best suit the characteristics of the engineering-geological profile and physical-mechanical properties of the soil strata (Pérez de Corcho and Machado 2016). In saturated fine soils, settlement increases significantly for sustained stresses over time. Theories such as Terzaghi's have been developed to evaluate these settlements. When the soil underlying the foundation is clay, prior measures must be taken so that the building does not reach excessive settlements.

Due to the gradual consolidation of clays, the compressibility of these strata has received special attention in recent years. Recently, some universities in South America have reported methods, theories, and computer tools for estimating settlement and distribution (Delgado and Quevedo, 2008; Díaz and Tomás, 2016) to control excessive settlement and reduce foundation risks.

Nowadays, thanks to technological advances, computer tools are used to evaluate primary consolidation. In 2010, Orozco and Equihua published a paper that included the Boussinesq solution for a uniformly stressed polygon.

The possibilities for extending the above-mentioned spreadsheet are varied and include the evaluation of entries by primary consolidation using the simplest and most practical solutions. In order to facilitate the use of these Excel sheets, solved examples and user queries are shown (Orozco and Equihua 2012).

2. Materials and Methods

After examining the stability limit states of building overturning, raft sliding, and foundation stability, Excel workbook DISBAL (Álvarez et al. 2018) was used to determine that primary consolidation was caused by the pressure applied by the raft foundation. This Excel book allows for comparison between the classic method of considering soil compressibility index and the layered summation method specified in the Cuban Design Standards for Shallow Foundation Geotechnical Engineering. This comparison helps to determine the size of the raft and avoid damage to the building or the services it provides.

In the particular case of the building under study, it provides important criteria for defining the number of floors to be built or for adjusting the foundation design. The following steps are used to check the limit state of deformation of the soil:

- Classical method considering the compressibility index.
- Method of the summation of layers in the Cuban standard for surface foundations.
- Comparison of the settlements by both procedures.

2.1 Geotechnical experimental investigations

It is assumed that the building is located in the geological engineering profile of the Civil Engineering Laboratory of the Oriental University, where measurements were conducted by the National Applied Research Corporation of Santiago, Cuba. The experimental studies published by Cabrera and Bella (2007) are summarized in Tables 1 and 2, as well as Figure 1a. The settlement depth is set at 2.15 m, located on the first elastic layer (clay), and the physical and mechanical parameters appear on the profile in Figure 1b.

The strata up to 9 m depth are high compressibility clays (CH) overlying low compressibility clays (CL). The average number of blows per foot (Nspt), obtained from the penetration test up to 7 m depth, refers to a hard consistency, being very hard below this depth. The soil compressibility indices (Cc) obtained from the consolidation test are between 0.14 and 0.22 and the expansivity indices (Cs) are between 0.02 and 0.06. Table 3 shows the preconsolidation ratio (OCR) values up to 6 m, confirming that the soil behaves as preconsolidated, with OCR values above 1.

2.2 Characterization of the building used in the study

A reinforced concrete public building with a width of 30 m and a length of 36 m, and a module of 7.20 m × 6 m, equipped with 3.30 m of pillars, and reinforced by a double gantry and ductile shear wall system for seismic action. Its height is variable, analyzing primary settlement for sub variables between three to eight floors. The basic raft and SAP 2000 NL version 19 are used to obtain stresses at the center of raft's gravity (Figure 1c), exported to an DISBAL Excel workbook.

The increase in seismic requirements is believed to be caused by vertical seismic acceleration on the ground, which is used to check the overturning stability, sliding, and stability of the ground, while the primary settlements are only used for gravity loads, including long-term live loads.

Table 1. Average values of soil physical-mechanical parameters per meter depth (Cabrera and Beira 2007)

Est.	z	LL	LP	Nspt	ω	Ic	γ_f	γ_d	γ_s	e_o	S
(m)	(%)	(%)	(Golpes)	(%)		(kN/m^3)	(kN/m^3)	(kN/m^3)		(%)	
R	1	64.5	25.6	15	23.6	1.1	18.3	14.8	26.9	0.70	79.0
R	2	63.1	24.6	22	24.4	1.0	19.3	15.5	26.9	0.62	69.0
R	3	56.5	24.4	16	25.6	1.0	18.6	14.8	26.6	0.72	76.0
1	4	60.3	24.6	29	29.8	0.9	18.5	14.2	26.8	0.72	85.0
1	5	56.9	28.2	21	35.8	0.7	17.8	13.1	26.8	0.92	83.0
1	6	81.7	31.8	20	34.0	1.0	17.8	13.3	26.9	0.84	90.0
1	7	80.3	30.8	21	41.9	0.8	16.8	11.9	27.2	1.29	88.5
2	8	74.3	27.6	23	22.3	1.1	18.2	14.9	27.3	0.84	75.0
2	9	54.2	24.5	22	20.4	1.1	19.6	16.2	27.4	0.69	83.0
3	10	49.4	24.2	58	19.7	1.2	20.3	17.0	27.2	0.60	90.7

Note: Est.: stratum, R: filling, z: depth, LL: Liquid limit, LP: plastic limit, ω: humidity, Ic: consistency index, eo: pore rate, S: saturation

Table 2. Edometric modulus Em (kPa) according to consolidation tests in the experimental field of civil engineering (Cabrera and Beira 2007)

Vertical pressure (kPa)	Edometric modulus Em (kPa)					
	Depth (m)					
	1 m	2 m	3 m	4 m	5 m	6 m
200	6686	8373	8924	5018	3987	10766
400	6434	9221	9256	5555	5742	11673
800	9354	11328	11893	7188	7765	11770

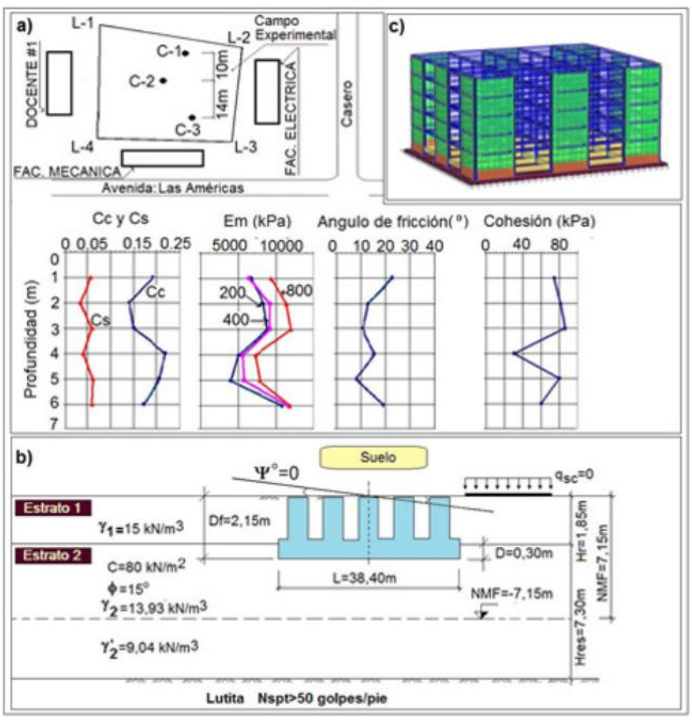

Figure 1. Data for the geotechnical design of the raft (Cabrera and Beira 2007). a) Soil mechanical parameters. b) Engineering-geological profile for the building location site and assumed depth of slump for the raft foundation. c) Structural model. Five-story variant. SAP 2000 version 19.

Table 3. Pre-consolidation ratio of OCR soil (Cabrera and Beira 2007)

Depth (m)	1	2	3	4	5	6
OCR	9.5	4	3.5	2.4	2.12	1.95

2.3 Methods for calculating primary consolidation

2.3.1 Classical method considering the compressibility index

The classical method for the calculation of primary consolidation, summarized by Braja (2008), is based on the preconsolidation ratio:

$$OCR = \frac{\sigma_c'}{\sigma_o'} \quad (1)$$

Note: σ_0': Effective vertical pressure (kPa), σ_c': Preconsolidation pressure (kPa), OCR≤1: Normally consolidated land, OCR>1: Preconsolidated soil.

For normally consolidated clays showing a linear e-log$^{\sigma'}$ ratio (Figure 2a). (Note: $\triangle\sigma=\triangle\sigma'$ at the end of consolidation)

$$\Delta e = C_c\,[\log(+\Delta\sigma') - \log\sigma_o'] \quad (2)$$

Note: C_c: Compression index (slope of graph e-log$^{\sigma 0'}$), $\triangle e$: Change of the void ratio.

Then the primary consolidation S is calculated:

$$S = \frac{C_c H}{1+e_0}\log\frac{\sigma_o' + \Delta\sigma'}{\sigma_o'} \quad (3)$$

Note: S: Primary consolidation (m), H: Stratum thickness (m), e_o: Initial void ratio.

For preconsolidated clays (Figure 2b), if $\sigma_0'+\triangle\sigma'\leq\sigma_c'$, then the e-log$\sigma'$ field variation will be along the line cb, of which the slope will be approximately equal to the slope of the laboratory discharge curve.

The slope of this curve is commonly used to obtain the coefficient of expansivity (C_S). Then:

$$\Delta e = C_s[\log(\sigma_o' + \Delta\sigma') - \log\sigma_o'] \quad (4)$$

$$S = \frac{C_s H}{1+e_0}\log\left(\frac{\sigma_o' + \Delta\sigma'}{\sigma_o'}\right) \quad (5)$$

If $\sigma_o'+\triangle\sigma' > \sigma_c'$, then:

$$S = \frac{C_S H}{1+e_0}\log\frac{\sigma_c'}{\sigma_o'} + \frac{C_c H}{1+e_0}\log\frac{\sigma_o' + \Delta\sigma'}{\sigma_c'} \quad (6)$$

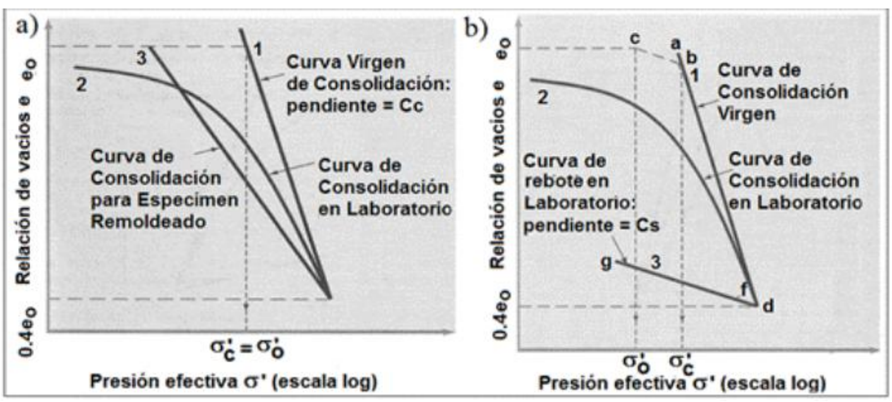

Figure 2. Primary consolidation of clays (Braja 2008). a) Normally consolidated clay of low to medium sensitivity. b) Preconsolidated clay of low to medium sensitivity.

If the e-logσ' curve is given, it is possible to take △e from the graph for the appropriate range of pressures, which can be substituted directly into the general equation to calculate the settlement (S). The calculation of settlement requires the fitting of consolidation curves; a recent procedure derived from the Juarez-Badillo theory is proposed by Medina and Melis (2003).

2.3.2 Layer summation method in the Cuban standard

This method is used for any soil property and works from a discretization of the model, by means of a heavy average, analyzing three points in each sub-stratum of the compressible stratum. The steps to follow are as follows:

- Define active power and divide the compressible stratum into sub-strata.
- The definition of active power is that the stress caused by applying a load is approximately 20% of the effective stress caused by the self-weight of the soil.
- Calculate gross pressure P, net pressure P' and influence factor Jz (Quevedo 1994, 1989; cited by Pérez de Corcho and Machado 2016).
- Calculate stresses due to imposed load σ_{zp}' and self-weight σ_{zg}' in the vertical direction passing through the characteristic points P_c of the foundation (X_{pc}=0.37l), for the upper (H_{is}), middle (H_{ie}) and lower (H_{ii}) boundary of each stratum.
- Calculate the variation of unit strain (ε) for the points mentioned above in each substratum (Quevedo 1994, 1989 and Broche 1994; cited by Pérez de Corcho and Machado 2016).
- Calculation of the absolute settlement for the characteristic point:

$$S_i = \sum_{i=1}^{NE} \left[\frac{H_i}{6}(\varepsilon_{is} + 4\varepsilon_{ic} + \varepsilon_{ii})\right] \quad (7)$$

Note: NE: Number of sub-strata below the sill level for active power (Ha), Hi: Thickness of substratum i, ε_{is}: Variation of the vertical unit strain at a point of the upper boundary of layer i, referred to the characteristic point, ε_{ie}: Same, but in the center of stratum i, ε_{ii}: Same, but at the lower boundary of stratum i.

- In soils with E_0 as deformational parameter.

$$\varepsilon = \frac{\sigma_{zp}'}{E_0} \quad (8)$$

Note: σzp': Effective vertical pressure increase produced by the imposed loads for the soil point where the settlement is evaluated.

3. Results and Discussion

3.1 Classical method considering the compressibility index

Absolute settlements due to primary consolidation were calculated by the classical method using the DISBAL Excel Book (Table 4), from the results of the consolidation test at the depth of analysis, for the sub-variants between three and eight stories. The preconsolidation pressure estimated from the compressibility curve (Figure 3) was considered, which was obtained from the consolidation tests performed on the soil samples taken in the field meter by meter up to the depth of 6 m.

Table 4. Absolute settlement by the classical method for the five-story building variant. Excel workbook DISBAL

Stratum	z	e_o	C_s	C_c	σ'c	J_i	/	/	S
	(m)				(kPa)		(kPa)	(kPa)	(m)
1	0.0	0.682	0.06	0.2	190	1.000	61.16		
1	0.5	0.682	0.06	0.2	190	0.999	61.12	37.76	0.0149
1	1.0	0.608	0.06	0.2	191	0.996	60.91		
2	1.0	0.608	0.06	0.2	191	0.996	60.91		
2	1.5	0.608	0.06	0.2	191	0.987	60.38	51.29	0.0126
2	2.0	0.710	0.06	0.2	185	0.973	59.48		
3	2.0	0.710	0.06	0.2	185	0.973	59.48		
3	2.5	0.710	0.06	0.2	185	0.952	58.23	64.81	0.0098
3	3.0	0.691	0.06	0.2	187	0.927	56.69		
4	3.0	0.691	0.06	0.2	187	0.927	56.69		
4	3.5	0.691	0.06	0.2	187	0.899	54.96	78.33	0.0082
4	4.0	0.908	0.06	0.2	270	0.868	53.11		
5	4.0	0.908	0.06	0.2	270	0.868	53.11		
5	4.5	0.908	0.06	0.2	270	0.838	51.22	91.86	0.0061
5	5.0	0.828	0.06	0.2	275	0.807	49.34		
6	5.0	0.828	0.06	0.2	275	0.807	49.34		
6	5.5	0.828	0.06	0.2	275	0.777	47.52	103.01	0.0054
6	6.0	0.828	0.06	0.2	275	0.748	45.77		
7	6.0	0.828	0.06	0.2	275	0.748	45.77		
7	6.5	0.828	0.06	0.2	275	0.721	44.12	111.79	0.0047
7	7.0	0.828	0.02	0.2	275	0.696	42.56		
Note: Absolute settlement (m) = 0.0617									

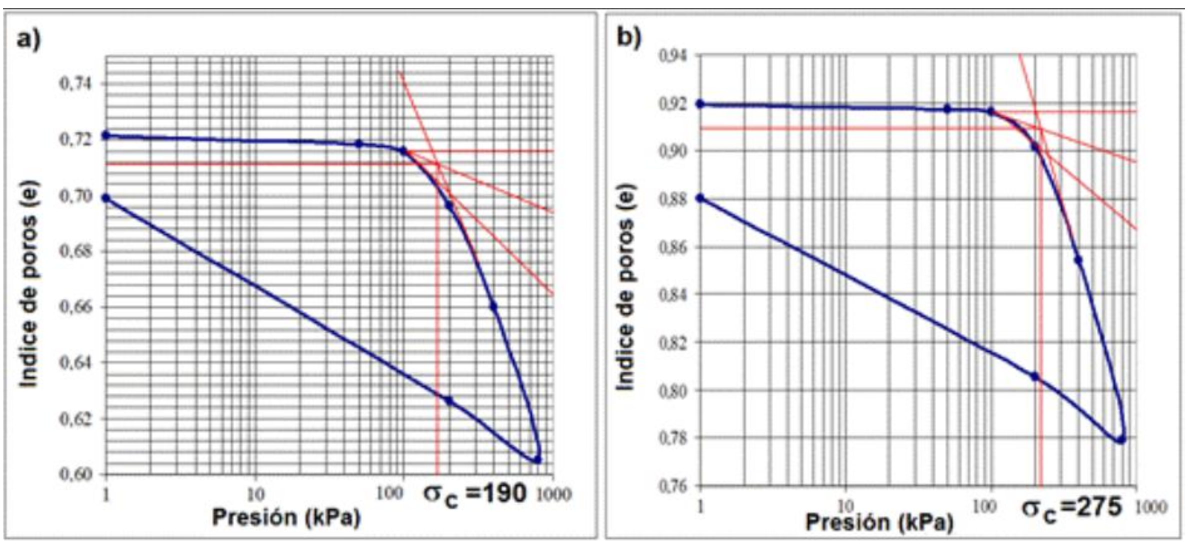

Figure 3. Preconsolidation pressure obtained from consolidation tests. Experimental field of Civil Engineering (Cabrera and Beira 2007). a) Depth of 3 m. b) Depth of 5 m.

The cumulative settlements evaluated by the classical method for the characteristic point (Table 4) are lower than those for the center of gravity and corner point of the foundation, which is also provided by the DISBAL Excel Book. The absolute cumulative settlements for the center of gravity of the foundation and for the corner points practically do not differ, because the imposed stresses discrepancy with depth for both points is very small. This is closely related to the active power, which results from the engineering-geological characteristics of the selected soil profile.

The active power is relatively small in relation to the dimensions of the basin, so that the influence coefficients, which determine the variation of the imposed stresses for the points mentioned above, vary very little with depth. It can also be seen that the external stress of the studied architectural variants can be considered to be relatively low; Please note that at the characteristic point at a depth of 2.5 meters, the applied stress is already lower than the effective stress of the soil (Table 4). According to the consolidation test, the soil belongs to pre-consolidated soil.

3.2 Method of the summation of layers in the Cuban standard

The absolute settlements were calculated by the layer summation method using the DISBAL Excel Book (Table 5 and Figure 4) for the sub-variants between three and eight stories, considering the variation of the soil deformation modulus obtained from edometric tests performed in the field meter by meter up to a depth of six meters.

The results are highly dependent on the estimation of the soil deformation modulus, which is assumed to be constant for each of the substrata. A good approximation will give results close to those of the classical method. Based on the edometric tests, for the lower substrata, higher deformation moduli are assumed than those of the upper substrata (Table 5).

Table 5. Absolute settlement by the sum-of-layers method for the five-story building variant. Excel workbook DISBAL

Stratum	Es (kPa)	z (m)	z/B	Ji	Aσ (kPa)	ε_i	S (w)
1		0.0	0.0000	1.000	61.15	0.0087	
1	7000	0.5	0.0154	0.999	61.12	0.0087	0.0087
1		1.0	0.0309	0.996	60.90	0.0087	
2		1.0	0.0309	0.996	60.90	0.0087	
2	7000	1.5	0.0463	0.987	60.37	0.0086	0.0086
2		2.0	0.0617	0.973	59.47	0.0085	
3		2.0	0.0617	0.973	59.47	0.0085	
3	7000	2.5	0.0772	0.952	58.22	0.0083	0.0083
3		3.0	0.0926	0.927	56,69	0.0081	
4		3.0	0.0926	0.927	56,69	0.0081	
4	7000	3.5	0.1080	0.899	54.95	0.0079	0.0078
4		4.0	0.1235	0.868	53.11	0.0076	
5		4.0	0.1235	0.868	53.11	0.0048	
5	11000	4.5	0.1389	0.838	51.22	0.0047	0.0047
5		5.0	0.1543	0.807	49.34	0.0045	
6		5.0	0.1543	0.807	49.34	0.0045	
6	11000	5.5	0.1698	0.777	47.52	0.0043	0.0043
6		6.0	0.1852	0.748	45.77	0.0042	
7		6.0	0.1852	0.748	45.77	0.0042	
7	11000	6.5	0.2006	0.721	44.11	0.0040	0.0040
7		7.0	0.2160	0,696	42.55	0.0039	

Note: Absolute settlement (m) = 0.0464

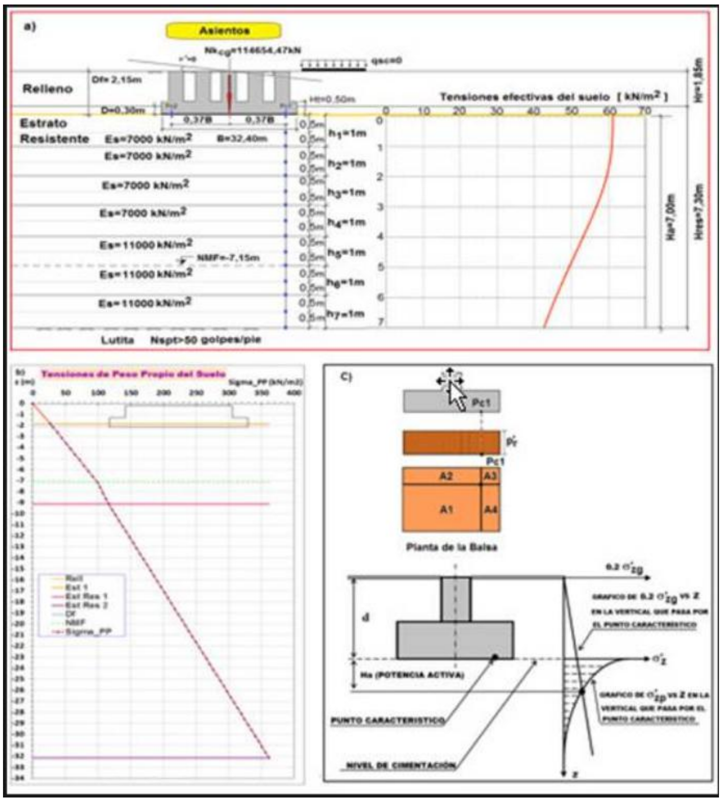

Figure 4. Primary settlement calculation. Method of summation of layers. a) Imposed soil stresses (Excel DISBAL book). b) Effective self-weight stresses of soil (Excel DISBAL book). c) Active depth of soil according to the Cuban standard.

3.3 Comparison of the settlements check by both methods

From the evaluation of the accumulated absolute settlement up to the active soil power, the following can be summarized:

- The settlements by the classical method for the raft center of gravity and for the corner points do not differ practically, as the imposed stresses for both points diverge little with depth. The active power is small in relation to the dimensions of the raft, so its influence coefficients vary little with depth.
- The settlements by the classical method for the characteristic point, for which the settlements of the rigid and flexible foundations are considered approximately equal (Figure 4), are lower than those of the center of gravity and corner point, since their imposed stresses decrease more with depth.
- The settlements according to the classic method are greater than those of the simplified method that considers constant deformation modulus for each of the sub-strata, since the accumulated primary settlements for the variants between three and eight stories are less than 8 cm, the maximum value specified in the Cuban standard for the building studied (Figure 5a). According to the classical method, the total primary settlement is met up to the seven-story variant. For the eight-story building it does not comply, although the difference is relatively small for practical purposes (Figure 5b).
- Considering a constant deformation modulus to calculate the main consolidation recommended by the Cuban standard can provide a settlement that is smaller than the absolute settlement obtained using compressibility and expansion indices, which is an aspect that projectors need to consider when checking the deformation limit state (Figure 5).
- For the studied variants, the absolute seating positions of the two methods showed an approximately linear change with increasing number of layers. This is reasonable because the load increases linearly with the number of layers, resulting in lower applied stress. In addition, these stresses are always lower than the linear stress of the soil, mainly due to the size of the foundation raft.

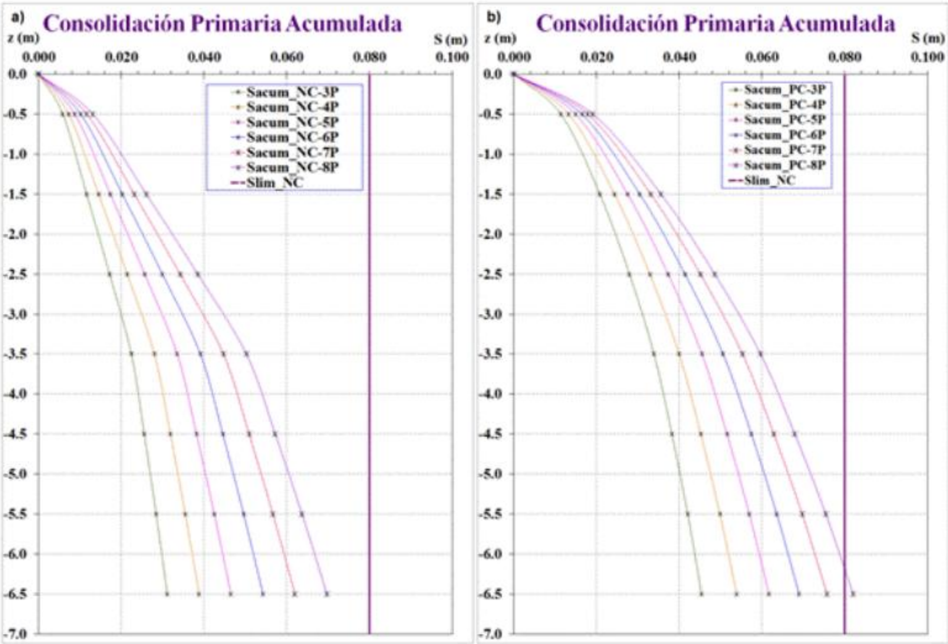

Figure 5. Comparison of primary consolidation for the building variant studied for a variable number of stories between three and eight stories. a) Sum-of-layers method. Excel workbook DISBAL. b) Classical method. Excel book DISBAL.

4. Conclusions

For soil research based on tensile and experimental testing to characterize the stress-strain behaviour of soil, the Excel book DISBAL allows for a more comprehensive evaluation of primary consolidation, as it can compare the results of classical methods with the results of the layered summation method in the Cuban standard. For case studies, the software provides two methods for appropriate evaluation of soil deformation limit states for any building model, thereby accelerating project outcomes. By using the compressibility index to calculate the main settlement and comparing the results of the classical program with the Cuban standard program, it is confirmed that strict soil research is necessary to rationalize the design of raft foundations.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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