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Development of a Program for Calculating Soil Settlements Using Classical Geotechnical Methods: A Case Study in the City of Pucallpa

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Abstract - The calculation of soil settlements is essential to guarantee the stability of structures in varied soils. Although classical geotechnical methods are used, such as elasticity theory and Terzaghi consolidation, the manual calculation of complex settlements can be laborious, making the use of specialized software necessary. In this context, Settle Classic was developed, an innovative program that allows settlement calculations without requiring commercial licenses and has a user-friendly interface that makes it easy to learn theoretical principles. The program was used in a case study in Pucallpa to obtain the total settlement experienced by the soil when a university infrastructure is built on it, for which the soil properties, foundation data and external load were entered, obtaining a total settlement of 6.018 cm, which indicates that this settlement exceeds the permitted limit for slabs established for this project (5.04 cm). Likewise, when validating the program with Settle 3D, a margin of error of 0.36% was shown for the settlement calculation of the case study, which validated the precision and reliability of the developed program. Additionally, the layer method was carried out in the developed program, dividing a stratum into several sub-strata, observing that the total settlement presents a slight variation as the number of sub-strata increases, which provides a value closer to the reality. On the other hand, the calculation of immediate settlement in granular soils was validated with a manual calculation using elasticity theory giving a percentage error of 0.37%. Therefore, the program developed Settle Classic is recommended for the calculation of immediate and consolidation settlements as it provides reliable results and is convenient for civil engineering students to verify their manual calculations.

Keywords**:** settlement, elasticity theory, Terzaghi consolidation theory, Settle 3D, Settle Classic, case study

1. Introduction

The calculation of soil settlements is fundamental to guarantee the stability and durability of structures on soils of various characteristics, since precision in these calculations is crucial to avoid structural failures [1]. Traditionally, classical geotechnical methods, such as elasticity theory and Terzaghi's consolidation theory, have been used to calculate settlements in soils [2]. However, to calculate complex settlements manually is laborious for those seeking to perform calculations quickly and correctly, often requiring specialized software.

In Cario, in the case of the Qasr Palace, the Plaxis 3D program was used to model and analyze the settlements of historical structures built on saturated clay soils caused by fluctuations in the water table [3]. In addition, in a section of the Magistral Zaza Canal, located in Cuba, linear settlements in shallow foundations on partially saturated soils were analyzed considering different degrees of saturation for which the ABAQUS program was used [4]. Likewise, settlements in plate-pile foundation systems on clay deposits in the city of Bogotá were analyzed, using a three-dimensional finite element model [5]. On the other hand, in two studies in Cuba, settlement calculations were carried out considering the classic Terzaghi method without using specialized software [6],[7]. In this sense, in 2023, surveys were carried out among civil engineering students and professionals in Costa Rica, revealing that 85% consider it important to have a mobile application to facilitate settlement calculations by primary consolidation in cohesive soils [8].

For this reason, the proposal is to develop a program based on classical theories as an alternative to current programs that use finite elements, which may require a high level of technical specialization, which limits its accessibility for many professionals and students who are not familiar. with its operation.

The main contribution of the developed program (Settle Classic) is that it is focused on improving the learning experience, allowing both students and professionals to acquire a deeper knowledge of the theoretical principles involved in soil settlement, while obtaining results. precise and practical. In addition, it offers an effective alternative to perform settlement calculations without depending on licenses or commercial programs that are not as accessible.

2. Case study

The clay soil of the city of Pucallpa is known for its high compressibility, which poses a challenge for infrastructure construction due to the potential for differential settlement [9]. The paper focuses on calculating the settlements that occur in the clay soil where a new university infrastructure is planned to be built. To calculate the settlements, the parameters obtained from the soil mechanics study carried out at the site and the water table at a depth of 7 m are considered. This information includes data on the proposed foundation, which are detailed in Table 1, and the soil properties in Table 2.

Table 1: Foundation data and external loading.

Type	**Foundation slab**
Depth (Df)	1.00 m
Length (L)	61.1 m
Width (B)	23.1 m
Applied load (q_o)	8 ton/m2

Table 2: Properties of each soil stratum.

Height (m)	**γ (g/cm3)**	**γ_{sat} (g/cm3)**	**SUCS**	**e_0**	**Cc**	**Cs**	**σ'_P (kg/cm2)**
0 - 1	1.95	-	CL	-	-	-	-
1 - 2	2.03	-	CL	0.45	0.170	0.021	2.44
2 - 3	2.03	-	CL	0.66	0.250	0.031	2.09
3 - 4	2.03	-	CL	0.69	0.260	0.033	1.92
4 - 5	2.03	-	CH	0.80	0.300	0.038	2.96
5 - 6	2.03	-	CH	0.74	0.280	0.035	3.66
6 - 7	2.03	-	CH	0.69	0.260	0.033	3.31
7 - 8	-	1.88	CH	0.64	0.240	0.030	4.01
8 - 9	-	1.88	CH	0.64	0.240	0.030	3.84
9 - 10	-	1.88	CL	0.53	0.200	0.025	3.31
10 - 11	-	1.88	CL	0.56	0.210	0.026	3.14
11 - 12	-	1.88	CL	0.58	0.220	0.028	2.62
12 - 13	-	1.88	CH	0.80	0.300	0.038	3.66
13 - 14	-	1.88	CH	0.69	0.260	0.033	4.01
14 - 15	-	1.88	CH	0.77	0.290	0.036	4.18
15 - 16	-	1.88	CH	0.90	0.340	0.043	3.66

3. Tools, Methodology and Method

3.1. Tools

3.1.1. Settle Classic

Is the program developed for this article using MATLAB AppDesigner that facilitates the calculation of settlements in soils using classical geotechnical methods. Among its functionalities, it offers the customisation of projects, the selection of soil properties, the evaluation of soil stresses and stress increments, as well as the calculation of immediate and primary consolidation settlements. It also incorporates concepts that explain the calculation process and allows you to print out the detailed steps to obtain the results. All this is designed to foster a deeper understanding of the theoretical principles governing settlement calculation.

3.1.2. Settle 3D

Is an advanced geotechnical software for soil settlement analysis that allows modelling of stratified soils and application of various types of loads, such as structures or embankments, to calculate soil behaviour under these conditions, and offers 3D simulations that provide a detailed visual representation of settlements over time, facilitating the interpretation of the results [10].

3.2. Methodology

The methodology used in the developed programme (Settle Classic) to determine the settlement of soils is based on a numerical approach that combines both elasticity theory and Terzaghi's consolidation theory. The elasticity theory is used to model the initial behaviour of soil under elastic loads, which is especially useful in non-cohesive soils, such as sands and gravels [11]. On the other hand, Terzaghi's consolidation theory is for evaluating settlements in cohesive soils, such as clays, where the process of expulsion of pore water causes settlements over time [12].

3.3. Method

The structure of the developed Settle Classic program follows an organized sequence of steps for settlement calculation for the case study, which are detailed below:

Step 1: General Setup

First, the name of the project, the method to be used for the settlement calculation and the location of the water table are entered.

Step 2: Soil properties

Then the properties of each soil stratum and the settlement analysis to be performed are entered, in this case the settlement analysis by primary consolidation is chosen, as shown in Fig. 1.

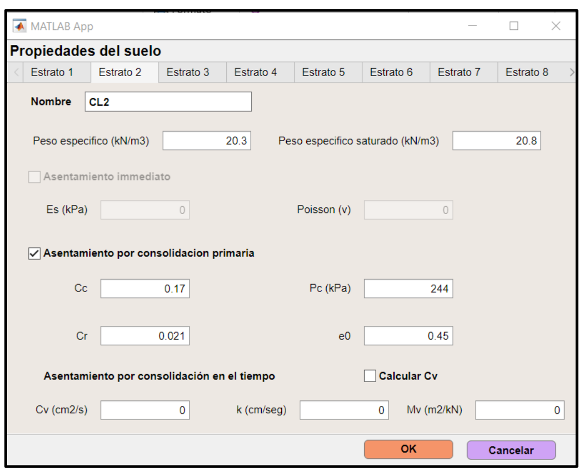


Fig. 1: Setting the soil properties in the Settle Classic program.

Step 3: Soil profile

Next, as shown in Fig. 2, the thicknesses of the different soil strata are edited and a graph of the soil profile is generated according to the layers and their names.

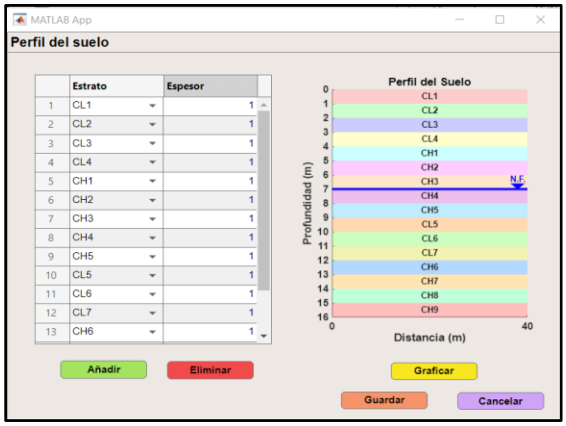


Fig. 2: Soil profile plotted in Settle Classic.

Step 4: Load

In this section, the load is defined, specifying that the foundation is a rectangular slab and the dimensions such as base, length, thickness, depth, and transmitted load are entered. The soil profile with the dimensions of the slab in the case study is shown in Fig. 3 below.

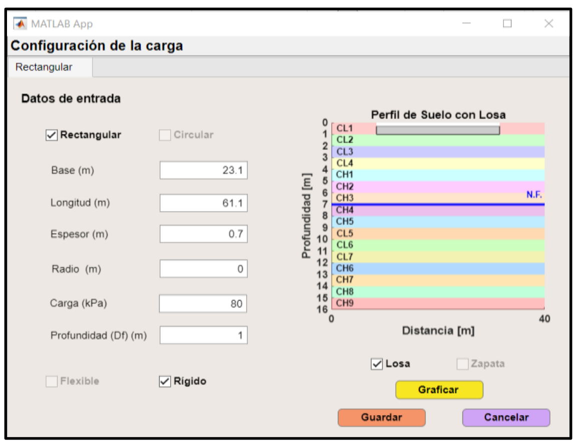


Fig. 3: Soil profile with the slab dimensioned in the Settle Classic program.

Step 5: Stresses in the soil

After entering all input parameters, this section shows a table with total stresses, pore pressure and effective stresses.

Step 6: Stress increment

In this phase, a table with the stress increments based on the Boussinesq theory for distributed loads is presented.

Step 7: Settlement

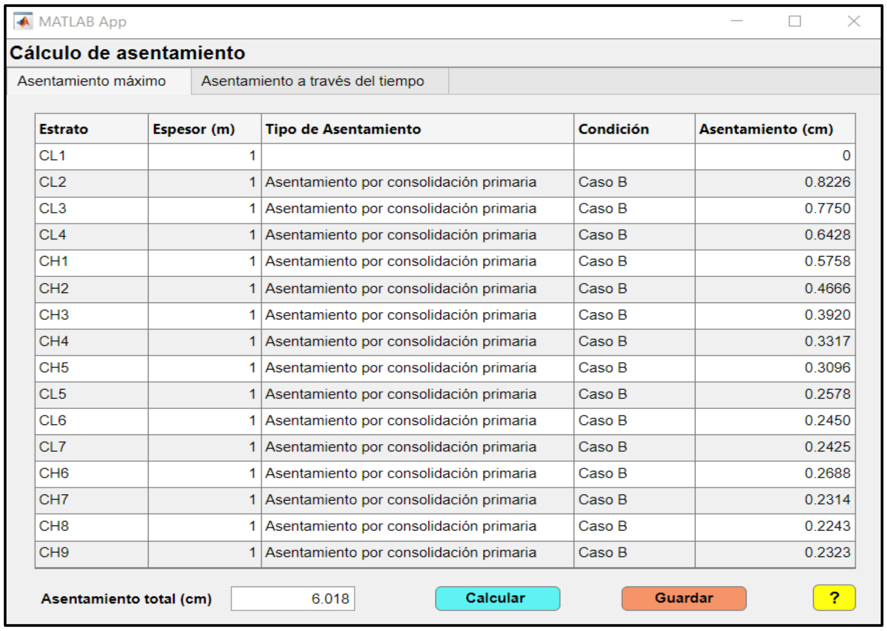
In this stage, the settlements of each stratum are shown in a table, indicating also the case of settlement by consolidation, in this case it presents the case B.

Step 8: General interface

Finally, the general interface displays the graph of the accumulated settlement vs. depth, terrain modelling and the result of the total settlement, which can be exported in PDF.

4. Results and Analysis
4.1. Results

The results of the settlement calculation per stratum for the Pucallpa case study, obtained using the Settle Classic software, are shown in Fig. 4. In addition, Fig. 5 shows the general interface, which includes graphs of the cumulative settlement (cm) as a function of depth (m) and terrain modelling, highlighting the settlement deformations in each stratum.


MATLAB App

Cálculo de asentamiento

Asentamiento máximo | Asentamiento a través del tiempo

Estrato	Espesor (m)	Tipo de Asentamiento	Condición	Asentamiento (cm)
CL1	1			0
CL2	1	Asentamiento por consolidación primaria	Caso B	0.8226
CL3	1	Asentamiento por consolidación primaria	Caso B	0.7750
CL4	1	Asentamiento por consolidación primaria	Caso B	0.6428
CH1	1	Asentamiento por consolidación primaria	Caso B	0.5758
CH2	1	Asentamiento por consolidación primaria	Caso B	0.4666
CH3	1	Asentamiento por consolidación primaria	Caso B	0.3920
CH4	1	Asentamiento por consolidación primaria	Caso B	0.3317
CH5	1	Asentamiento por consolidación primaria	Caso B	0.3096
CL5	1	Asentamiento por consolidación primaria	Caso B	0.2578
CL6	1	Asentamiento por consolidación primaria	Caso B	0.2450
CL7	1	Asentamiento por consolidación primaria	Caso B	0.2425
CH6	1	Asentamiento por consolidación primaria	Caso B	0.2688
CH7	1	Asentamiento por consolidación primaria	Caso B	0.2314
CH8	1	Asentamiento por consolidación primaria	Caso B	0.2243
CH9	1	Asentamiento por consolidación primaria	Caso B	0.2323

Asentamiento total (cm) 6.018 | Calcular | Guardar | ?

Fig. 4: Results of the settlement calculation of the case study elaborated in the Settle Classic program.

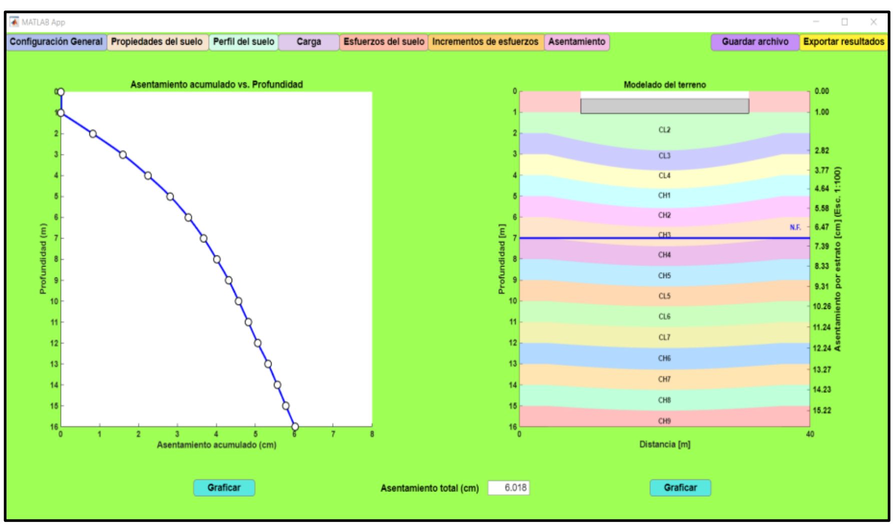


Fig. 5: Graphs obtained in the general interface of the Settle Classic program with the results of the settlement calculation.

4.2. Analysis of results

In Fig. 4, the settlement calculation for each stratum is detailed, observing that the settlement decreases with depth. This is due to the fact that, at greater depth, the effective stress of the soil is greater, which increases its bearing capacity, while the increase in load dissipates with depth.

In Figure 5, the graph on the left shows that as the depth increases, the settlements accumulate in each stratum, reaching a total settlement of 6.018 cm at 16 m depth, which exceeds the allowable limit for slabs established for this project [13]. This value is related to the high compressibility and plasticity of the clayey soil present in the city of Pucallpa, which puts the stability of the projected university infrastructure at risk, since excessive settlement could cause structural damage.

In view of this situation, it is necessary to consider solutions such as soil improvement or, failing this, to opt for deep foundations that transfer the loads to more competent strata, guaranteeing the safety of the structure.

5. Validation

Fig. 6 shows the modelling and the results of the settlement calculation of the case study in Pucallpa, carried out using the Settle 3D program to validate the result obtained with the developed program. For this purpose, the soil properties, the thickness of the strata and the load of the structure were entered, as was done in the Settle Classic program developed.

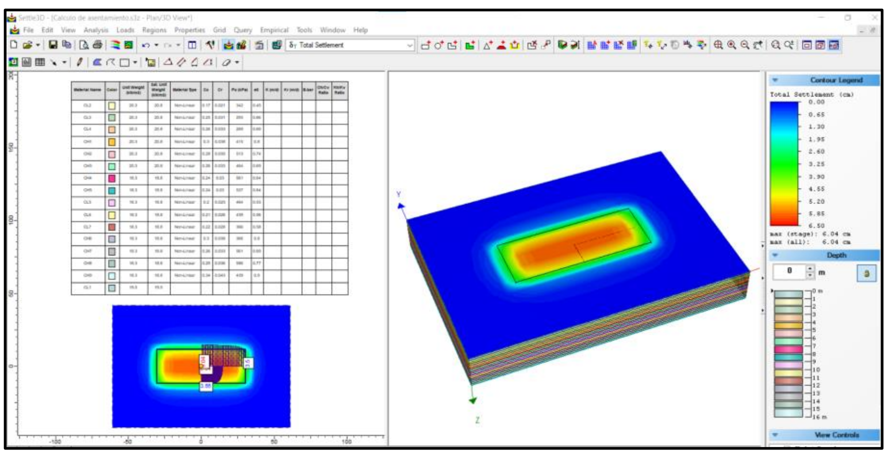


Fig. 6: Results of the settlement calculation of the case study elaborated in the Settle 3D program.

The comparison between the results obtained from Settle 3D and Settle Classic shows the total settlement of 6.04 cm and 6.018 cm, respectively, with a minimum difference of 0.022 cm, which represents a margin of error of 0.36% due to the fact that the Settle 3D program uses the layer method that allows dividing the strata into multiple sub-layers, which facilitates a more detailed calculation of the stresses at each depth level.

In the programme developed to analyse the variation of settlement using the layered method, a 6 m thick stratum was considered, dividing it into 2, 3 and 6 sub-strata, considering that the soil is preconsolidated (Case B). The calculated settlement for the complete 6 metres stratum was 2.221 cm. When divided into 2 sub-strata of 3 metres each, the settlement obtained was 2.237 cm; for 3 sub-strata of 2 metres, 2.238 cm was obtained and for 6 sub-strata of 1 metre, the value reached 2.245 cm. This analysis shows that by increasing the number of sub-strata, a better adjustment of the calculation is achieved, providing a value closer to the reality of the settlement that the soil will experience.

In addition, a practical exercise was evaluated using a soil with three clay strata, each with different properties and for different cases (B and C), to calculate the settlement by primary consolidation. This analysis yielded a margin of error of 1.42% between the developed Settle Classic program (with a settlement value of 14.1 cm) versus Settle 3D (which yielded a value of 13.9 cm). The difference in the results is due to the fact that each case has its own error percentage, which means that when several types of cases are used, the error percentage increases.

On the other hand, the calculation of settlements in granular soils was checked with the theory of elasticity using the equation of Skempton (1951) and Giroud (1968) with the data of an exercise [14]. The result of the manual exercise gives a settlement of 2.69 cm and with our developed program results in a settlement of 2.68 cm, giving a minimum difference of 0.01 cm, which represents a margin of error of 0.37%, due to the fact that the program does not round any value.

Finally, an exercise of a soil composed of sand and clay strata was verified, for which it was considered that the settlements in the sand strata are negligible for this calculation, because only settlements by primary consolidation were analysed, obtaining a result in the Settle Classic programme of 11.74 cm, in Settle 3D of 11.4 cm and manually 11.67 cm, giving a margin of error of 2.90% with Settle 3D and a 0.6% error with the exercise solved by hand. Therefore, the developed program is effective with the manual calculation because it considers the option of disregarding the calculation in a granular stratum that is required while the Settle 3D does not consider disregarding any stratum.

6. Conclusions

The Settle Classic program, developed in MATLAB AppDesigner, offers options for personalisation and detailed calculations, as well as an interface that facilitates learning and theoretical understanding. It also represents an accessible tool for users to perform settlement calculations without the need for commercially licensed software. This program considers soil stress analysis and stress increment at the midpoints of each stratum which are visualised in different windows. Additionally, the obtained results can be exported as a PDF file as a detailed report of the calculations.

This program focuses on applying Terzaghi and elasticity theories to calculate settlements in different types of soils. Although there are other theories that can also be used for this purpose, we have decided to concentrate on these two because the Terzaghi theory is fundamental for calculating consolidation settlement in cohesive soils, while the elasticity theory is adequate for granular soils.

For the case study, a total settlement of 6.018 cm was obtained, which exceeds the maximum limit allowed for slabs in this project (5.04cm), which could affect the stability of the planned university infrastructure. Therefore, it is essential to explore alternatives, such as soil improvement or the implementation of deep foundations, to ensure the safety and durability of the structure.

When validating Settle Classic and Settle 3D, a minimum difference of 0.022 cm was found, which represents a margin of error of 0.36% in the case study in the city of Pucallpa, due to the fact that the Settle 3D programme uses the layered method, which facilitates a more detailed calculation of the stresses at each depth level. However, these error percentages are small and don't have a considerable impact on the final result.

Likewise, in the programme developed, when analysing a 6 metres stratum by dividing it into 2, 3 and 6 sub-strata, considering that the soil is pre-consolidated (Case B), it was observed that the total settlement presents a slight variation as the number of sub-strata increases. These divisions allow a better adjustment in the calculation, providing a value closer to the reality of the settlement that the soil will experience when subjected to loads.

The settlement calculation for granular soils obtained in the programme developed using the equation of Skempton (1951) and Giroud (1968) shows a minimal difference of only 0.01 cm compared to the manual calculation, which corresponds to a margin of error of 0.37%. This small discrepancy is due to the fact that the program retains all decimals in the intermediate calculations, avoiding rounding and ensuring greater precision in the results.

In conclusion, Settle Classic is a free program that has been developed to allow both students and professionals to calculate settlements in a simple way, without the need to resort to commercial programs. Its user-friendly interface and its ability to perform detailed calculations make it an excellent choice for learning and verifying your manual calculations, as the programme incorporates the same considerations that are followed when manually calculating settlements by classical theories. Its low margin of error, validated against manual calculations and Settle 3D, makes it a reliable option to be used. Therefore, it is recommended to use this developed programme, as it facilitates learning and optimises the settlement calculation.

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