Numerical simulation of flooding process of a collapsible soil with raft foundation

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Abstract. Collapsible soils are those that suffer a considerable reduction in volume when exposed to an increase in water content, even without the addition of external loading. Numerical and experimental simulation of this phenomenon to understand the behavior of shallow and deep foundations is relatively complex, since it involves phenomena related to unsaturated soils and transient flow. In view of this, the present study aims to present the numerical simulation of the flooding process of a collapsible soil in the Federal District of Brazil (Geotechnical Experimental Field of the University of Brasilia), where was built a physical reference model consisting of a raft and a system of vertical drains. The simulation was carried out using the Finite Element Method in the Plaxis software, with the implementation of the Costa and Cavalcante hydraulic model, proposed in 2021. After comparing the results of the numerical analysis with those obtained in the field, it was observed that the model used managed to properly reproduce the flooding process carried out, in such a way that it can also be used to simulate numerically, together with an adequate mechanical model, the phenomenon of collapse and the behavior of more complex foundation systems in such a situation.

Keywords: flooding, raft, finite element method, collapsible soils.

1 Introduction

Soil mechanics has developed, since the beginning, directing its analyzes to the study of soils in totally dry or totally saturated conditions, however, these are only particular cases in which the material can be found, so that normally the soil is in unsaturated condition (Vilar [1]).

Among the phenomena addressed by the mechanics of unsaturated soils is soil collapse, which consists of a significant reduction in volume with a decrease in suction, caused by an increase in water content. Soils with this characteristic can be found in some places in some parts of the world, such as the Federal District of Brazil (León *et al.* [2]), where this research was carried out.

This work is part of a project involving FAPDF (Fundação de Apoio à Pesquisa do Distrito Federal) and the Programa de Pós-Graduação em Geotecnia at the University of Brasilia (PPGG), where physical and numerical simulations of soil collapse due to loading and flooding were performed using raft models.

Some studies have already been carried out involving the collapsible soil of the Federal District using the Finite Element Method to analyze rigid inclusions, however, with a simplified approach, that is, with the use of constitutive models that are not so assertive, especially with regard to the process of soil flooding (León [3]; Gomes [4]; Santiago [5]).

In view of this, this article seeks to present the numerical simulation of the flooding process of a collapsible soil in the Federal District, where a reference model of raft was built with a flooding system by drains, using Finite Element Method and the hydraulic model of Costa and Cavalcante [6] to simulate soil water flow.

2 Methodology

To carry out the numerical simulation of the flooding process of the collapsible subsoil, the Finite Element Method (FEM) was used with the Plaxis 2D software. The numerical model was elaborated to approximately represent the flooding system built together with a raft in the geotechnical experimental field of the University of Brasilia (CEG-UnB), located in Asa Norte, in Brasília.

The flooding system was installed in the built raft, with the presence of 12 cylindrical tubes with a diameter of 5 cm that go down to the end of the collapsible layer (3.5 m below ground level) and carry out, through holes in their walls, subsoil flooding. Figure 1 shows the raft before concreting, where it is possible to see the upper part of the flood system, while Fig. 2 presents the mesh of the axisymmetric model representing the local stratigraphy.

Figure 1. Upper part of the flood system builted in CEG-UnB.

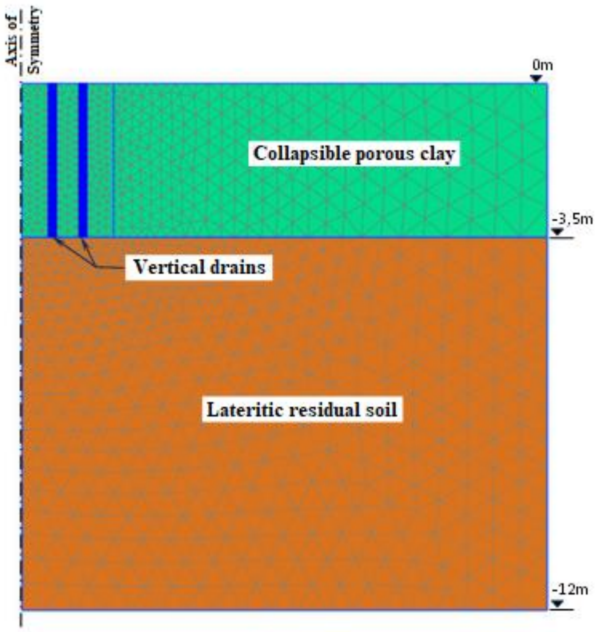

Figure 2. Axisymmetric model mesh.

Note that, treating it as axisymmetric, the flood system was modeled in Plaxis as “two circular flood walls”, represented in the software through elements called “Infiltration Well”. The wall with a smaller radius geometrically surrounds the four internal drains, while the wall with a larger radius encompasses the other eight drains. The radius of the inner wall is 0.7 m, corresponding to the distance from each of the four inner drains to the center of the raft, while the radius of the second wall is 1.4 m, which is the distance from the outer drains to the center of shallow foundation. This proposed representation in the axisymmetric system is shown in plan in Fig. 3.

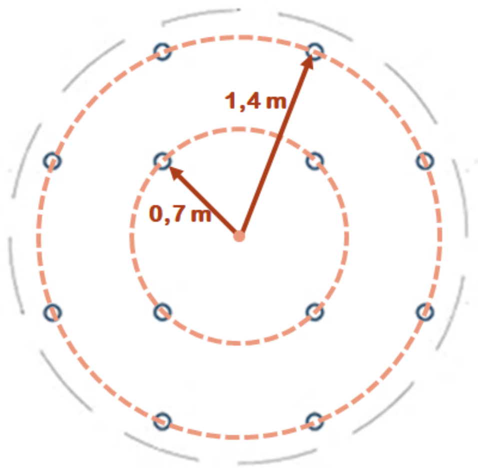

Figure 3. Plan representation of the proposed axisymmetric flooding.

The mechanical parameters and physical indices of the soil were obtained in the laboratory by Guimarães [7], while the determination of the horizontal and vertical permeability coefficients was carried out from two tests following the procedure of USBR 7300-89 (DOI [8]), from so that, from the average value of hydraulic conductivity calculated in this procedure, a parametric analysis was performed to obtain the flow versus time curve closest to the test points, considering a ratio between the horizontal (kh) and vertical permeability (kv) greater than one and different permeabilities between the two layers (k1 and k2). Figure 4 shows the flow versus time curve obtained as a result of the parametric analysis in comparison with the data sets from the two permeability tests performed.

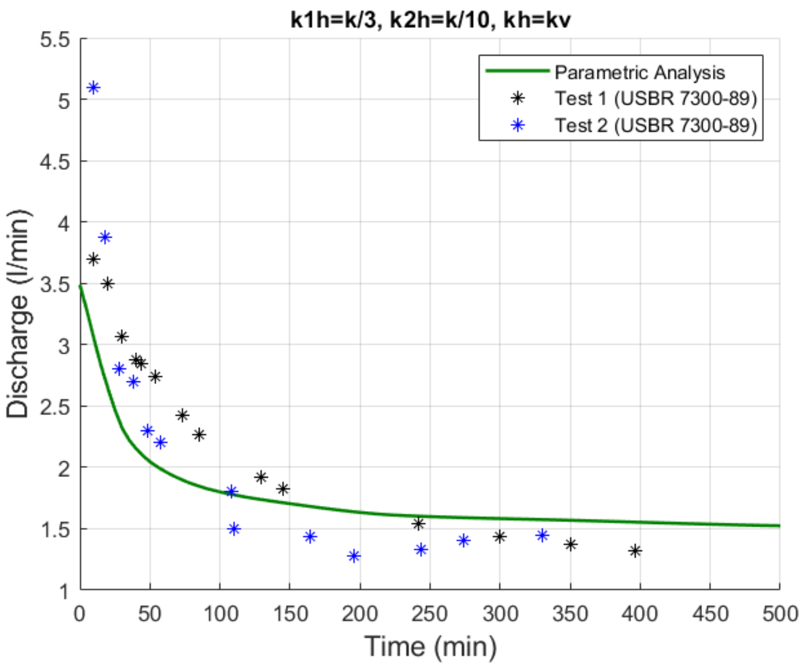

Figure 4. Flow versus time curve obtained from the parametric analysis.

In the same way, to determine the hydraulic loads as initial flow conditions, a parametric analysis was also performed, but this time with reference to the local humidity profile at a time close to the physical simulation.

2.1 Hydraulic model

To determine the characteristic curve and the k-Function, important instruments for the analysis of soil water flow in unsaturated conditions, the proposal by Costa and Cavalcante [6] was used. This model comes from the equations by Cavalcante and Zornberg [9] and consists of the bimodal representation of the soil water retention curve and the k-Function, respectively eq. (1) and eq. (2), both formulated from linear superposition.

$$\theta(|\psi|)=\theta_r+(\theta_s-\theta_r)[\lambda\cdot\exp(-\delta_1|\psi|)+(1-\lambda)\cdot\exp(-\delta_2|\psi|)] \quad (1)$$

$$k(|\psi|)=k_s[\lambda\cdot\exp(-\delta_1|\psi|)+(1-\lambda)\cdot\exp(-\delta_2|\psi|)] \quad (2)$$

Where:

θ, k [m/s] and ψ [Pa] are volumetric water content, hydraulic conductivity and suction, respectively;

θ_s, θ_r and k_s are fixed values, corresponding to the saturated and residual volumetric water content and the saturated hydraulic conductivity, respectively. The first two were obtained from Silva [10] and the saturated permeability was the value derived from the parametric analysis in the horizontal and vertical directions. Its measurement units are analogous to water content and hydraulic conductivity;

λ, δ_1 and δ_2 are dimensionless parameters of the model and which, as well as in the hydraulic model by Cavalcante and Zornberg [9], also have a physical meaning. These parameters were adjusted according to Silva's characteristic curves [10], so that based on their determination, it was possible to plot the characteristic curve and the k-Function for the studied subsoil, as shown in Fig. 5.

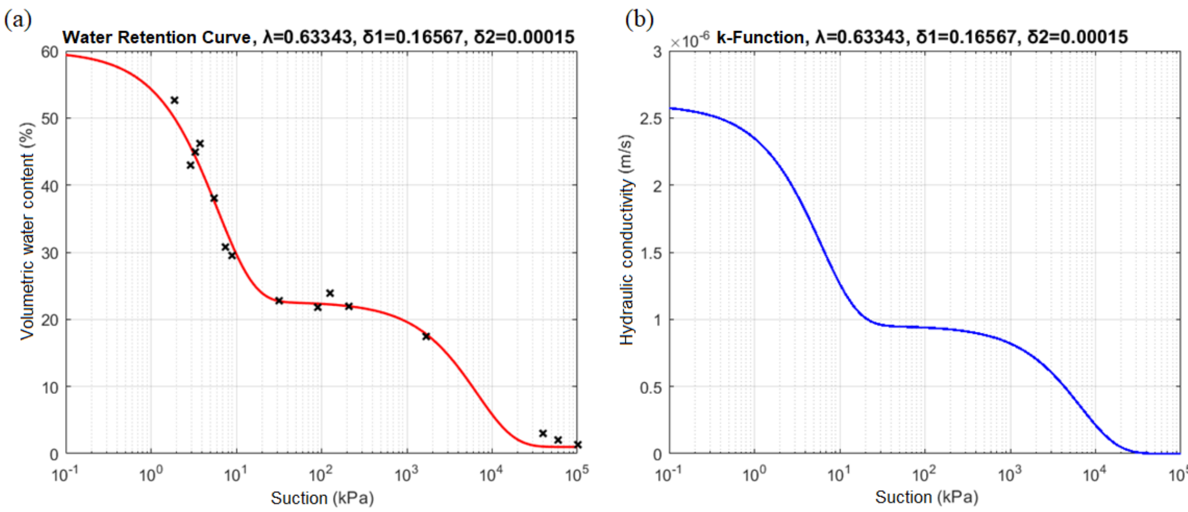

Figure 5. (a) Soil water retention curve. (b) k-Function.

The test points by Silva [10] are plotted in Fig. 5-a to get an idea of how close the curve adjusted by the model was, so that, having the parameters of the hydraulic model and the value of the saturated hydraulic conductivity from the parametric analysis, the k-Function was also built, as shown in Fig. 5-b.

Once the soil parameters and hydraulic conditions were defined, a numerical simulation of the flooding process was carried out with the flow values recorded in the physical simulation divided into five intervals, given the impossibility of inserting a continuous flow versus time curve in the Infiltration Wells. The curve registered in the physical simulation and the five representative steps used are illustrated in Fig. 6.

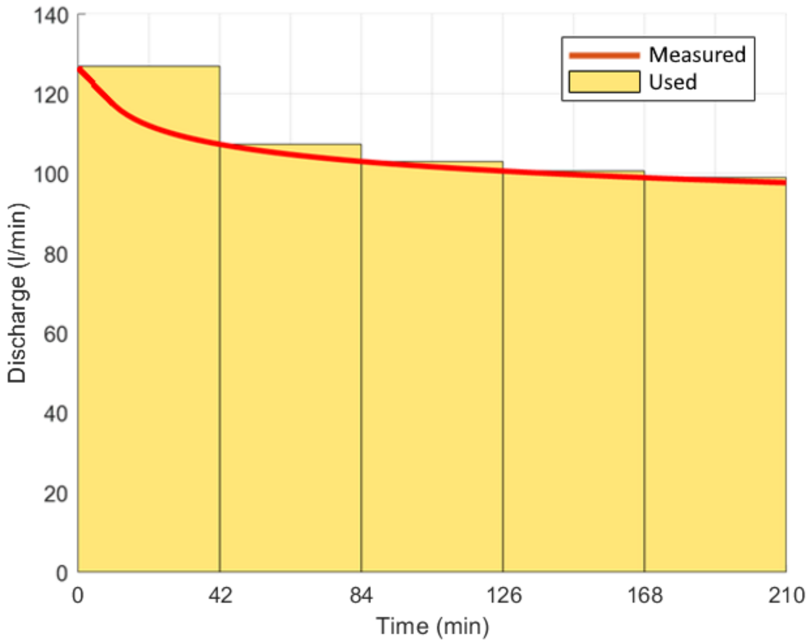

Figure 6. Variation of measured and used discharge values.

It is observed that the flow decreases with time, due to soil saturation, starting with a maximum value of 126.9 l/min ($2.12 \cdot 10^{-3}$ m³/s) and ending with an established flow of 99 l/min ($1.65 \cdot 10^{-3}$ m³/s). Furthermore, through the installed flowmeter, in addition to the instantaneous flow values, the total infiltrated volume of 20.8 m³ was recorded, consistent with that obtained in the approximation used.

3 Results and discussions

Following the described methodology, a numerical simulation of the subsoil flooding process was carried out considering the times and flows shown in Fig. 6, as well as the model by Costa and Cavalcante [6] and the initial conditions of hydraulic head and permeability obtained and presented in Tab. 1.

Table 1. Initial conditions obtained from parametric analysis.

Parameter	Value	Unit
Horizontal permeability coefficient	$1.3 \cdot 10^{-6}$	m/s
Vertical permeability coefficient	$2.17 \cdot 10^{-7}$	m/s
Maximum hydraulic head	-10.2	m
Minimum hydraulic head	-10.6	m

Having carried out the numerical simulation of the subsoil flooding process, the saturation bulb shown in Fig. 7 was obtained shortly after the end of the 3.5 hours (210 min) of flooding.

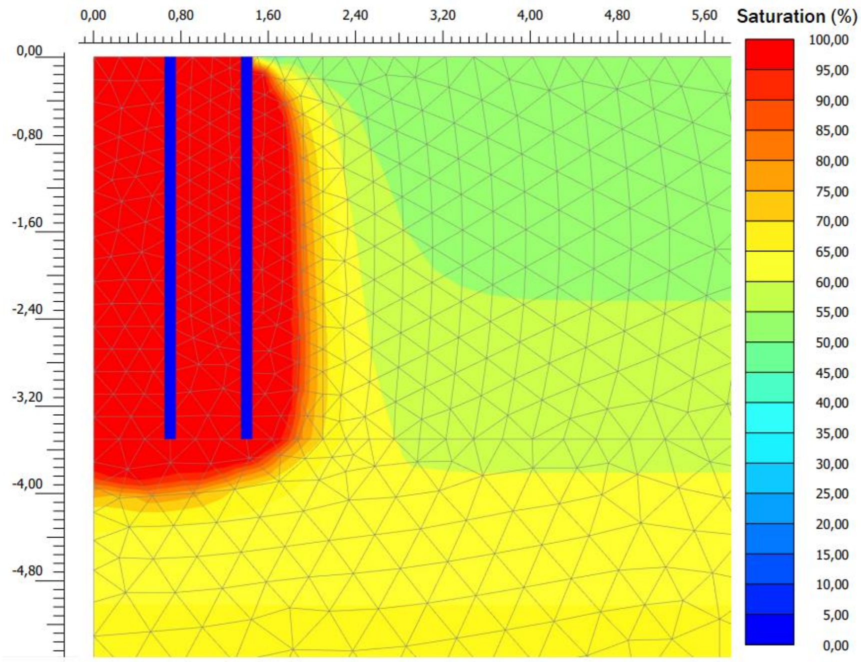

Figure 7. Saturation bulb obtained.

It is observed that, at the end of the flooding process, a completely saturated zone was obtained from the numerical simulation, comprising a bulb with a radius equal to little more than 1.7 m. This value was similarly observed in the field in the physical model, where an upwelling of water was noted in a region greater than 20 cm from the edge of the raft, which has a radius of 1.5 m, that is, a saturated zone with a radius of about 1.7 m, as illustrated in Fig. 8.

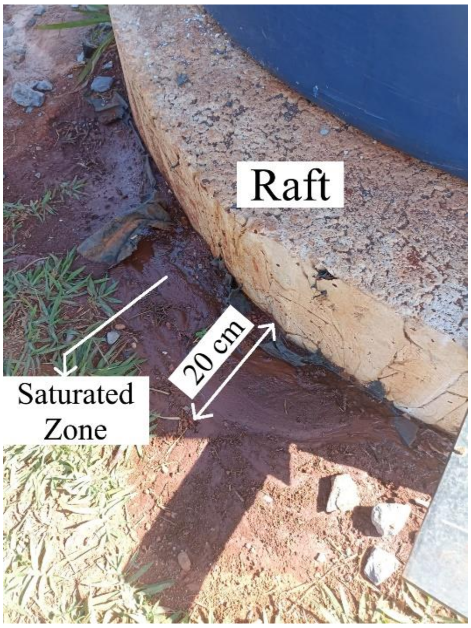

Figure 8. Saturated zone observed in the physical simulation

Based on this result, it appears that the methodology used, although simplified, was able to properly reproduce what was observed in the physical simulation involving the subsoil flooding process. Therefore, this methodology can be used for the simulation of subsoil collapse, together with constitutive models that can simulate the mechanical behavior of porous clay, since to correctly analyze the phenomenon of collapse it is necessary to correctly consider the flow and deformability of the soil.

4 Conclusions

In view of what was obtained from the numerical simulation, it is verified, from the comparison with the physical model carried out in the CEG-UnB, that the model by Costa and Cavalcante [6], as well as the methodology used to obtain the initial conditions and the necessary parameters, showed a good assertiveness in reproducing the flow of water in the subsoil submitted to the flooding process through the drains.

It is also concluded that, having managed to reproduce subsoil flooding well, the model can also be used as a component to simulate the process of soil collapse together with an adequate mechanical model, such as the Barcelona Basic Model (Alonso *et al.* [11]).

Using said methodology, in future works physical and numerical simulations will be carried out involving more complex foundation systems subjected to flooding and collapse processes.

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