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# Numerical and experimental analysis of isolated footings on collapsible soil under different moisture and preloading conditions

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**Article**

**Keywords**
Isolated footing
Flooded soil
Static load test
Stress-settlement curve
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3D numerical modeling
Collapsible soil

**Abstract**

To ensure structural safety, understanding the behavior of foundations on collapsible soils under moisture variation is crucial. This study evaluates the performance of isolated footings installed in collapsible soil from Uberlândia (MG) under two scenarios: directly flooded without preloading, and preloaded before flooding. Both footings were subjected to slow static load tests and analyzed through three-dimensional numerical modeling using RS3 software. The results demonstrated a significant reduction in bearing capacity when flooding occurred prior to loading (up to 64%), compared to a 24% reduction when preloading was applied before inundation. The stress–settlement curves further revealed that preloading led to stiffer soil response and higher bearing capacity, with a 53% increase at 25 mm settlement compared to the non-preloaded case. These findings highlight the effectiveness of preloading in improving the performance of shallow foundations on collapsible soils under saturated conditions.

## 1. Introduction

In Brazil, the use of shallow foundations, such as rafts and isolated footings, directly supported on the soil has long been a common practice for various types of constructions. However, this widespread practice, often carried out without proper soil characterization, has led to the occurrence of pathologies related to these foundations when placed on collapsible soils, especially when exposed to increased moisture content. In Uberlândia, located in the Triângulo Mineiro region, the territorial extension is characterized by lateritic soils with low bearing capacity and high susceptibility to deformation, mainly due to moisture increase, which can result in structural collapse ranging from cracks to severe damage in buildings. Based on this, it is essential to conduct specific analyses of these soils prior to the implementation of foundations. In this regard, the performance of load tests, which are in situ tests, allows for the evaluation of the interaction between the foundation and the supporting soil.

It is commonly understood that all foundations inevitably undergo settlements during and after the completion of the structure in which they are employed. These settlements may vary depending on the magnitude of the stresses dissipated into the foundations and the deformability of the soil on which they are placed. Based on prior studies of local and design characteristics, such settlements are expected and tend to stabilize or even cease after a certain period. However, in areas where the subsoil lacks adequate bearing capacity, significant settlements may occur, exceeding the tolerance limits of the structural system in use, which has contributed to the development of pathologies in various constructed structures. These settlements, known as "collapse settlements," tend to occur primarily in soils classified as collapsible.

Due to their saturation characteristics, porosity, and high void ratios, collapsible soils may, according to Cintra & Aoki (2009), experience a collapse of their structure as a result of increased moisture content or degree of saturation under constant applied stress. This produces the collapse phenomenon, leading to sudden settlements that are added to the normal settlements. These collapse settlements can occur at any point during the service life of the structure, and their occurrence depends solely on the presence of a water source capable of flooding the soil on which the foundation is set. This flooding causes the dissipation of the soil's matric suction, eliminating the "apparent" cohesion component and thereby significantly reducing the shear strength, ultimately resulting in the collapse of the soil structure.

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From that point on, several studies have been developed with the aim of analyzing and better understanding the collapsibility of this type of soil and the behavior of foundations constructed on it, through both load tests on real-scale prototypes as observed in the studies by Carneiro (1999), Freitas Neto (2013), Garcia (2015), Xavier (2018), Garcia & Albuquerque (2019), Oliveira (2022), Lopes (2023), Lopes & Garcia (2024), Saraiva Júnior (2024) and Pereira (2025) as well as through numerical simulations, as seen in the works of Resende & Garcia (2021), Oliveira et al. (2022), Pereira & Garcia (2023), Azevedo & Garcia (2023), among others.

The Brazilian foundation standard ABNT (2022) emphasizes that, in the case of collapsible soils, the possibility of saturation must be considered, which may occur due to factors such as water pipe leaks or rising groundwater levels, among others.

Furthermore, the standard states that these characteristics must be considered both in the design phase and in the construction method. Based on this, it is important to highlight the need to experimentally and numerically analyze the behavior of foundations under different moisture and preloading conditions, to contribute to the understanding of the performance of foundations resting on collapsible soils.

## 2. Materials and methods

### 2.1 Experimental site and geotechnical properties of materials

The foundations under study were constructed at the Experimental Field for Soil Mechanics and Foundations (CEMSF) of the Federal University of Uberlândia (UFU), located at the Santa Mônica Campus in the city of Uberlândia, MG (Figure 1).

In order to determine the mechanical characteristics of the local soil layers, Standard Penetration Tests (SPT) and Light Dynamic Penetrometer (DPL) tests were conducted, resulting in the values shown in Figure 2. In addition to these tests, Oliveira (2022) carried out further geotechnical investigations for soil characterization and in situ load tests on real-scale models, which generated the parameters listed in Table 1.

### 2.2 Loading test setup

For the analyses, an isolated footing with a diameter of 1 m and a height of 0.20 m was constructed, matching the same characteristics of the isolated footing tested by Oliveira (2022), both located in the same experimental field.

Since this study focuses on the behavior of foundations on collapsible soil in flooded conditions, priority was given to performing the load test on the isolated footing with the soil directly flooded, without a preloading stage while the soil moisture was in its natural state. This procedure was adopted to analyze the soil behavior under its initial stress conditions without a history of prior loadings before the flooded test, thereby allowing the acquisition of data for a comparative analysis with the isolated footing foundation tested by Oliveira (2022) under natural soil conditions and after flooding following preloading.

For the load test of the isolated footing with the soil directly in a flooded state, a prior flooding was conducted for a period of 24 hours before the test (Figure 3a), with the water flow stopped at the start of the test (Figure 3b). To

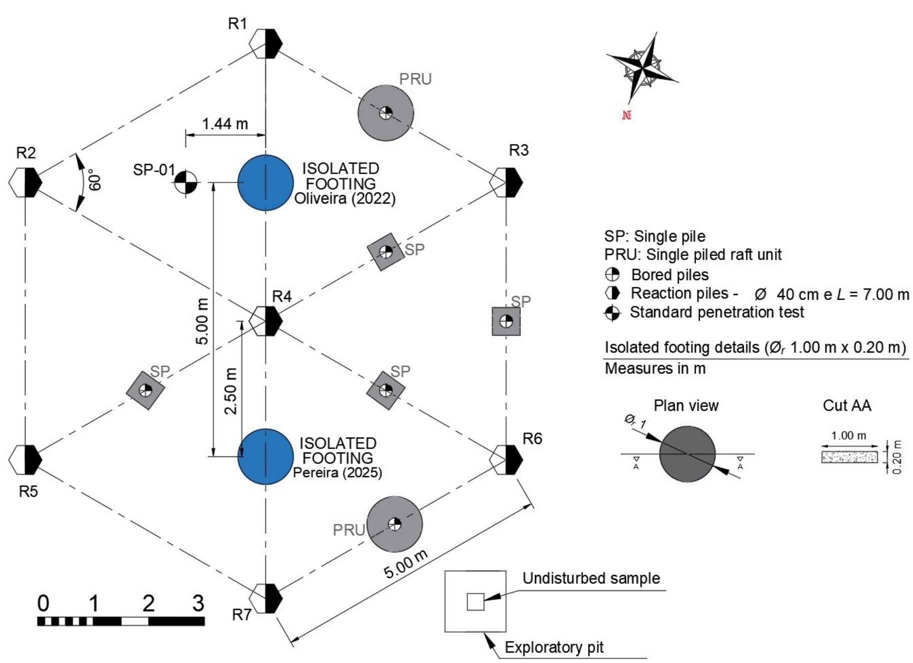


**Figure 1.** Plan view of the test site.

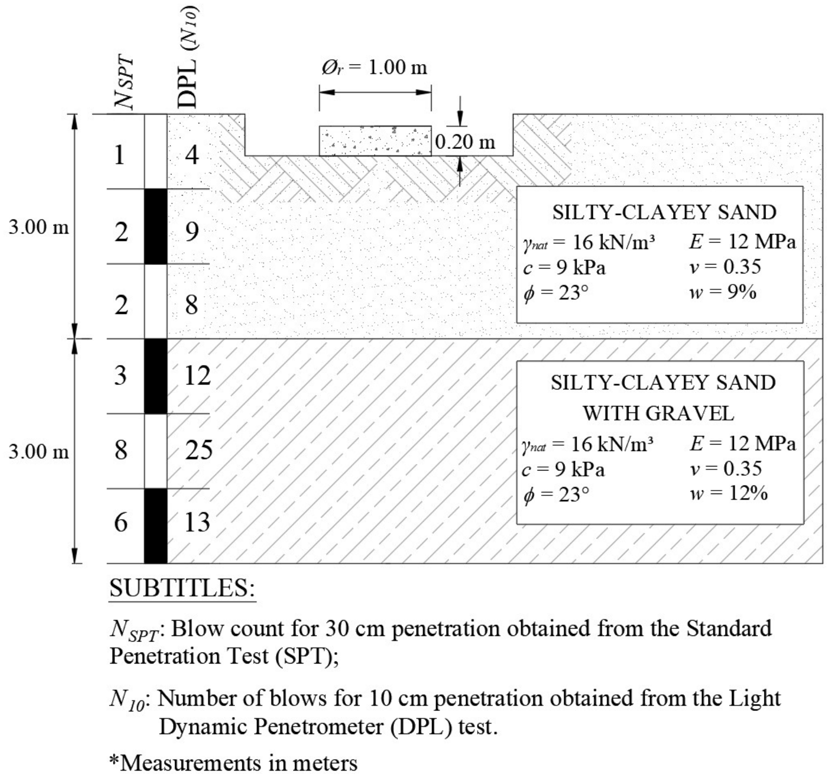


**Figure 2.** Geotechnical profile of the experimental field obtained by SPT.


**Figure 3.** Load test on isolated footing with soil in flooded state: (a) Pre-flooding of soil; (b) Water flow ceased and test started.

**Table 1.** Soil Parameters.

| Soil | Thickness | $\gamma_{nat}$ | $c$ | $\phi$ | $E$ | $\nu$ | $w$ | $N_{SPT\ average}$ | $N_{10\ average}$ |
|---|---|---|---|---|---|---|---|---|---|
| | [m] | [kN/m³] | [kPa] | [º] | [MPa] | [-] | (%) | (blows) | (blows) |
| Silty-clayey sand | 0 to 3 | 16 | 9 | 23 | 12 | 0.35 | 9 | 2 | 7 |
| Silty-clayey sand with gravel | 3 to 6 | 16 | 9 | 23 | 12 | 0.35 | 12 | 6 | 17 |

Adapted from Oliveira (2022). Legend: see List of symbols and abbreviations.

eliminate the influence of contact between the footing's lateral surface and the soil, an excavation around the footing was carried out prior to the flooding. This excavation also served to prevent changes in the moisture content, or suction, of the soil beneath the footing's sides. Additionally, it facilitated the flooding process by ensuring it was possible to maintain a water layer around the footing.

For the execution of load tests on shallow foundations, the ABNT (2019) standard requires that displacements be read immediately after the application of the load corresponding to the stage, followed by readings at 2 min, 4 min, 8 min, 15 min, 30 min, 1 h, and subsequently at 1-hour intervals from the start of the stage until stabilization is reached. However, since this isolated footing was also constructed to evaluate its isolated behavior and to compare it when used as a footing cap for a piled raft foundation element, the test readings were standardized following the same time intervals adopted for deep foundation tests. A slow loading procedure was applied, with readings taken at 5 min, 10 min, 15 min, and 30 min intervals, and additional readings, if necessary, taken every 15 minutes until settlement stabilization was observed at the respective stage load.

Adopting the same criteria used to establish the measurement time intervals during the test, it was also standardized that the load increments should follow the guidelines of ABNT (2020) regarding load testing of deep foundations. These increments were performed in equal and successive stages, with the load applied at each stage not exceeding 20% of the design working load for the test pile. Each load stage was maintained until displacement stabilization and for a minimum of 30 minutes. Based on this, load increments of 5 kN were defined, and the loading test was conducted until reaching a maximum settlement of 62 mm, which was sufficient displacement to characterize the failure of the isolated footing. Subsequently, the foundation was unloaded.

### 2.3 Bearing capacity

Over the years, several studies conducted through plate load tests combined with suction measurements have indicated that the bearing capacity of foundations constructed on collapsible soils is directly influenced by matric suction. This results in a loss of strength as the soil moisture content increases, causing a reduction in matric suction.

Costa (1999), also through plate load tests with an 80 cm diameter using slow maintained load (SML) and quick maintained load (QML) methods, demonstrated an increase in bearing capacity due to the increase in matric suction.

In shallow foundations, when evaluating the effect of suction on plates with diameters of 20 cm, 40 cm, 80 cm, and 150 cm, Vianna et al. (2007) identified significant relationships between the increase in allowable plate load and the soil's matric suction. Additionally, tests conducted with soil flooding revealed aspects of the soil's behavior under collapsibility conditions.

Oliveira (2022) through static load tests conducted in Uberlândia – MG on soil in its natural and flooded states for three types of foundations (isolated pile, isolated footing, and piled footing), observed reductions in the bearing capacity of piles ranging from 35% to 50% when flooding was applied to collapsible soils compared to the natural condition.

Through the stress versus settlement curve, it is possible to determine the allowable soil stress ($\sigma_{adm}$) for an allowable or tolerable settlement according to the characteristics of the superstructure. According to Albuquerque & Garcia (2020), this determination should be based on the most unfavorable value among the following criteria:

Failure Criterion:

$$\sigma_{adm} \leq \frac{\sigma_{rup}}{FS} \left(FS \geq 2\right) \tag{1}$$

If no failure occurs:

$$\sigma_{adm} \leq \frac{\sigma_{máx}}{FS} \left(FS \geq 2\right) \tag{2}$$

It is also possible to use the criterion from construction practices in the city of Boston, as reported by Teixeira & Godoy (2016):

$$Settlement\ Criterion : \sigma_{adm} \leq \begin{cases} \sigma_{10\,mm} \\ \dfrac{\sigma_{25\,mm}}{2} \end{cases} \tag{3}$$

where $\sigma_{10\ mm}$ is the stress observed on the stress versus settlement curve corresponding to a settlement of 10 mm, and $\sigma_{25\ mm}$ is the stress observed on the stress versus settlement curve corresponding to a settlement of 25 mm.

### 2.4 3D FEM numerical model

In order to compare the behavior and representativeness of the numerical model with the experimental results, the numerical model was constructed using the RS3 software by Rocscience, which employs the Finite Element Method (FEM) for solving three-dimensional models (Figure 4). The software package consists of three components: RS Modeler (pre-processing and modeling), RS Compute (processing), and RS Interpret (post-processing). This type of analysis is generally considered superior to two-dimensional analysis because it allows a more accurate representation of the problem geometry in a semi-space with length, width, and depth, accounting for volumetric properties and enabling a more detailed evaluation of the behavior of the object under loadings such as those in static load tests (SLT).

For the modeling, a semi-space with dimensions of 10 × 10 × 10 m was considered (Figure 4), aiming to ensure that the deformations at the boundaries of the semi-space were minimal compared to the deformations observed at the foundation element. Boundary conditions were applied by considering the top of the model as free for displacements, the lateral boundaries of the semi-space had their displacements constrained to zero in the XY directions, and the base was fixed in all XYZ directions, allowing only vertical displacement of the foundation.

Regarding the mesh for the numerical analysis of the three-dimensional model, tetrahedral elements with 10 nodes were adopted, whose representation of the numerical stress-strain curves proved to be more trustworthy to the curves observed in the experimental test results. These elements are, in turn, expansions of the 6-node elements used in the two-dimensional model extended to three dimensions. It is important to highlight that the mesh was refined progressively closer to the region of interest in order to improve the quality and representativeness of the computational analysis in this area.

For the numerical simulations, the Mohr-Coulomb failure criterion was adopted, as it is one of the most commonly used methods for technical modeling. Considering the various simulations performed, it was possible to plot the numerical load versus settlement curve of the test foundation, numerically refining the parameters adopted for the soil on which it was constructed, as shown in Table 2 and in the curves presented subsequently.

## 3 Analysis and results

### 3.1 Loading tests

The results obtained from the load test conducted in the experimental field with the soil in a flooded state are presented, compared to the results obtained by Oliveira (2022) in load tests with soil in its natural state, followed by the preloaded flooded test.

Through Figure 5, it is possible to evaluate the stress versus displacement curve (in black with filled ball) obtained from the static load test on the isolated footing with soil in a flooded state without preloading. In this test, a maximum load of 50 kN was applied, corresponding to a stress of 64 kPa, which caused a maximum displacement of 62.15 mm. According to the previously adopted proposition, in terms of allowable values, a bearing capacity was determined for a settlement of 25 mm at approximately 33 kPa, resulting

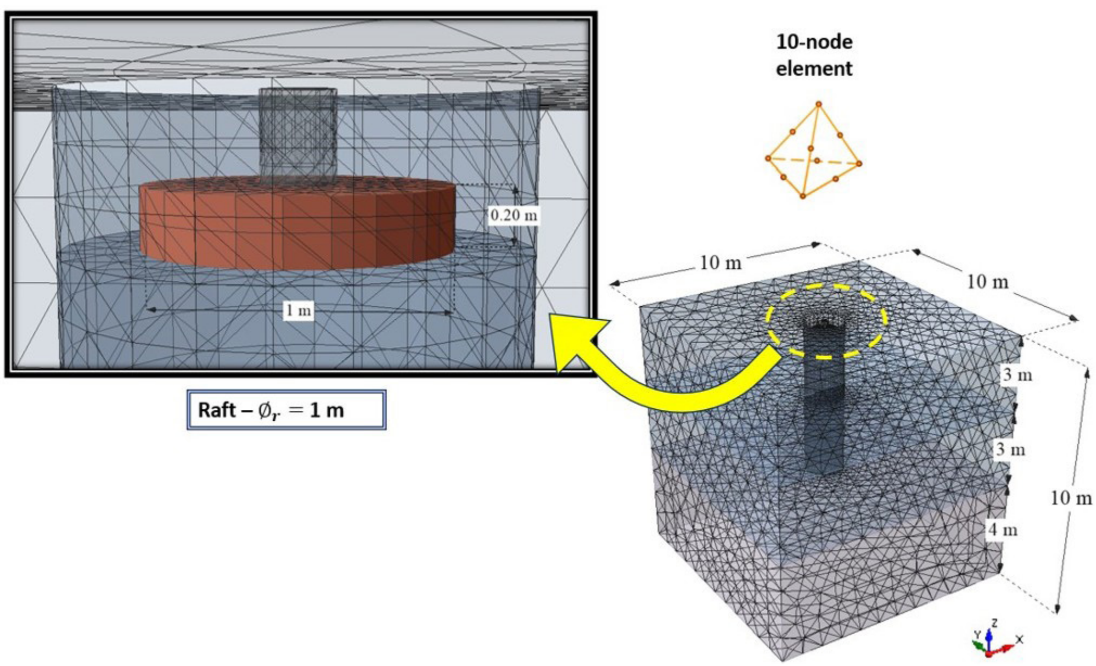


**Figure 4.** Three-dimensional FEM model of the mesh highlights densification in the foot region.

**Table 2. Soil parameters for numerical modeling RS3 –** Isolated Footing.

| Soil | Thickness | $\gamma_{nat}$ | $c$ | $c_{res}$ | $\phi$ | $E$ | $E_{res}$ | $v$ |
|---|---|---|---|---|---|---|---|---|
| | [m] | [kN/m$^3$] | [kPa] | [kPa] | [°] | [MPa] | [MPa] | [-] |
| Silty-clayey sand (In-situ) | 0 to 6 | 16 | 19 | 19 | 25 | 12 | - | 0.35 |
| | 6 to 10 | 16 | 20 | 20 | 30 | 15 | - | 0.35 |
| Silty-clayey sand (Flooded) | 0 to 10 | 16 | 1 | 1 | 20 | 2.4 | 1.05 | 0.35 |

Legend: see List of symbols and abbreviations.

in an allowable load of 17 kPa (*FS* = 2) with an allowable settlement of 6.46 mm.

Also, in Figure 5, the flooded isolated footing tested in this study (SP INUND EXP), performed on September 1st, 2022, is compared with the test conducted by Oliveira (2022), carried out earlier on August 3rd, 2021. In Oliveira's study, a single footing was used to perform two sequential load tests: first under the natural moisture condition and then, on the following day, under a flooded condition after 24 h of controlled inundation, which inherently resulted in a preloaded footing before flooding. In contrast, the SP INUND EXP was performed on a different footing of identical geometry and geotechnical characteristics, which was flooded prior to any loading, thus avoiding prior preloading. This distinction allows a direct assessment of the isolated influence of preloading on the flooded response, while fully preventing any hydraulic or mechanical interaction between the tests.

For comparison purposes, in addition to the results obtained in the flooded load test without preloading (SI-INUND-SPC-EXP) from this study, Table 3 also presents the values reported by Oliveira (2022) for the same foundation model under natural moisture conditions (SI-NAT-EXP) and under flooded conditions after preloading (SI-INUND-PC-EXP). The percentage ratio between the bearing capacities in flooded and natural conditions shows a pronounced reduction in strength when the footing is tested under flooding: approximately 24% reduction for the case with flooding after preloading, and approximately 64% reduction for the footing that was flooded prior to the beginning of the loading stage.

Furthermore, if the settlement accumulated from preloading is disregarded in the stress versus displacement curve obtained by Oliveira (2022) and compared with the curve from the present study Figure 5, it is observed that the footing tested with prior flooding without preloading exhibits a lower bearing capacity compared to the same footing tested flooded after preloading. This reduction is approximately 53% for the same settlement of 25 mm observed in both tests, with stresses of 33 kPa and 70 kPa, respectively. It is also noted in the curve with prior flooding without preloading that for the same load, the observed settlements are significantly greater

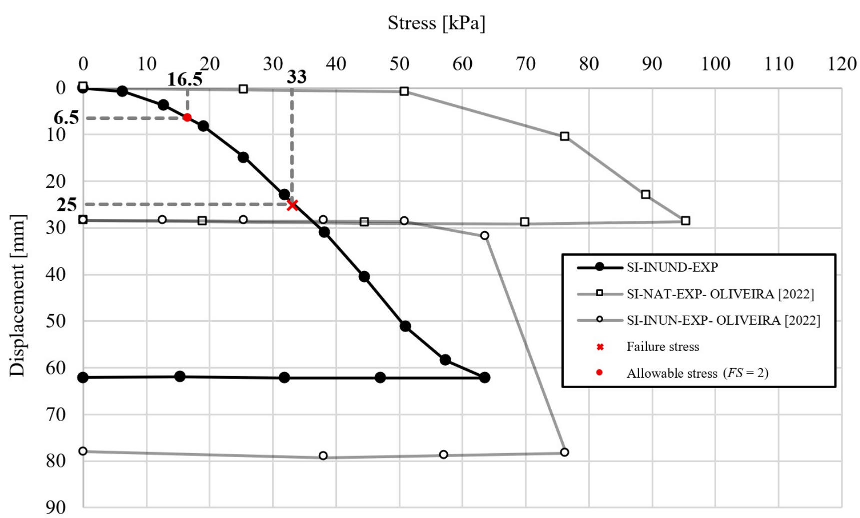


**Figure 5.** Stress versus displacement curve obtained by experimental testing of isolated footing in natural and flooded state, with and without preloading.

**Table 3.** Comparison of failure and allowable stress and allowable displacement in natural and flooded state with and without preloading.

| Foundation | $\sigma_{rup}$ (1) | $\sigma_{adm}$ (2) | $s_{adm}$ (3) | $\frac{\sigma_{inund}}{\sigma_{nat}}$ | $\sigma_{\downarrow}$ (4) | Reference |
|---|---|---|---|---|---|---|
| | [kPa] | [kPa] | [mm] | [%] | [%] | |
| SI-NAT-EXP | 92 | 46 | 3.45 | - | - | Oliveira (2022) |
| SI-INUND-PC-EXP | 70 | 35 | 0.13 | 76 | 24 | Oliveira (2022) |
| SI-INUND-SPC-EXP | 33 | 17 | 6.46 | 36 | 64 | Pereira (2025), Oliveira (2022) |

(1) Ultimate bearing stress for a displacement equal to 25 mm or with clear failure; (2) Allowable bearing stress considering for a safety factor of 2; (3) Allowable displacement corresponding to the allowable stress; (4) Percentage reduction in ultimate bearing stress under flooded conditions, with and without preloading, relative to the in-situ condition.

than those in the flooded curve with preloading, indicating a higher soil porosity with an increased void ratio.

The results obtained for shallow foundations reinforce the discussions already presented in literature by various authors such as Oliveira (2022), Saab (2022), Xavier (2018) and Agnelli (1992), who in their works observed a significant reduction in the load-bearing capacity of shallow foundations when subjected to flooded testing. A compilation of these results can be seen in Figure 6.

These results emphasize the importance of performing preloading and/or the removal and recompaction of the soil beneath shallow foundation bases, aiming to improve soil characteristics by increasing its bearing capacity and shear strength through the reduction of voids in its structure. As a consequence, this practice reduces the potential for consolidation during foundation loading, especially in scenarios where there is a risk of future flooding.

### 3.2 Numerical simulations

The numerical simulation using the finite element method, in a three-dimensional model of the isolated footing without preloading under flooded soil conditions (SI-INUND-NUM), was performed, and the load versus settlement curves obtained for the in situ flooded and numerical conditions are presented in Figure 7.

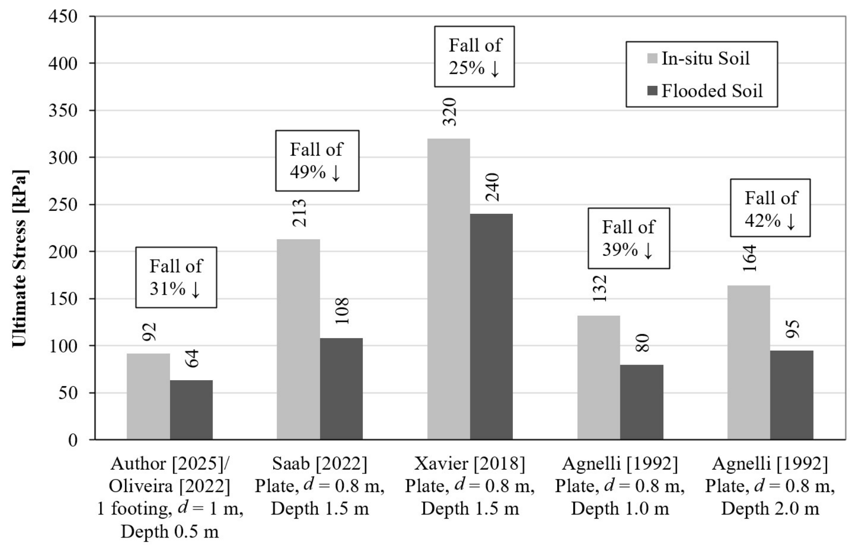


**Figure 6.** Comparison of experimentally obtained load capacity for direct foundations in-situ and flooded soil.

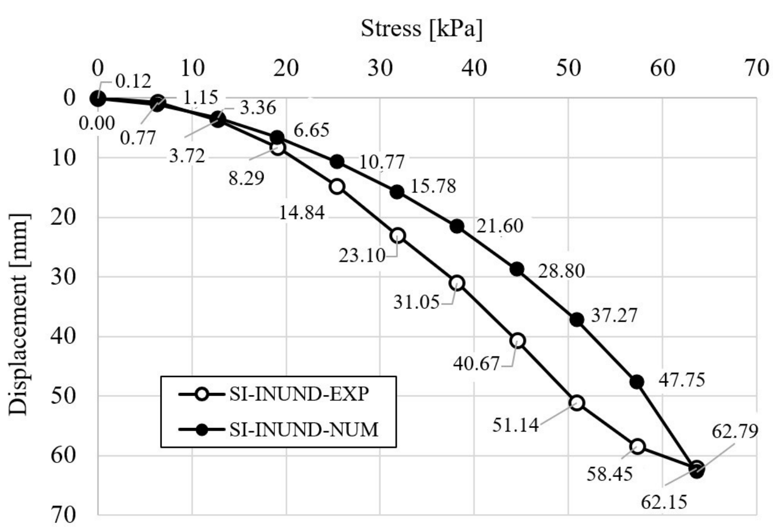


**Figure 7.** Stress versus displacement curve obtained by experimental and numerical testing of an isolated footing without preloading in a flooded state.

In the comparison between the experimental and numerical curves (Figure 7), it is observed that the numerical response shows a smoother and more continuous curvature, with smaller settlements. This behavior is consistent with the fact that the numerical model represents the flooded soil as a continuous medium with explicitly reduced strength and stiffness parameters (as listed in Table 2), already corresponding to the saturated state. In contrast, the experimental response involves a collapse phenomenon characterized by a sudden breakdown of the soil structure, which is inherently discontinuous under rapid suction loss. Therefore, the observed difference is not due to a lack of flooding representation in the model, but rather to the distinct physical nature of discontinuous collapse versus the continuous formulation of the finite element method.

## 4 Conclusion

In this study, foundations resting on collapsible soils in both in-situ and flooded states, with and without preloading, were analyzed. To this end, a load test was conducted on an isolated footing with a height of 0.20 m and a diameter of 1 m, resting on collapsible soil from Uberlândia (MG), flooded from the beginning and without preloading. The results were compared to those obtained by Oliveira (2022), who tested an identical footing to that in this article but which was initially preloaded and unloaded in its in-situ state, followed by flooding of the soil around the footing, and subsequently reloaded until failure.

The results indicated a significant reduction in the bearing capacity of the footings when subjected to tests in a flooded state compared to the footings tested in their in-situ state. This reduction was 24% when flooding occurred after preloading and 64% when the footing was flooded from the beginning of the first loading stage, i.e., without prior preloading. Analyzing the load versus settlement curves, it was also observed that the footing subjected to prior flooding without preloading exhibited a lower bearing capacity compared to the footing tested after preloading, with a reduction of approximately 53%.

The application of preloading on a footing resting on collapsible soil under in-situ moisture conditions ensured smaller settlements during loading under flooded conditions, demonstrating that the practice of excavating the soil beneath the base of shallow foundations followed by recompaction contributes to soil improvement. This results in an increase in bearing capacity due to the reduction of soil voids, especially in areas with collapsible soils subject to flooding conditions, thereby reducing the effects of soil collapsibility and its implications for foundations and, consequently, the building structure.

Regarding the numerical model developed using the RS3 computational tool, a slight variation was observed in the behavior of the numerical curve compared to the experimental curve. This difference is likely due to the way the numerical model represents the flooded soil as a medium composed of continuous bonds between soil, water, and air rather than as a discontinuous medium as observed in collapse situations. However, despite this variation, with mesh refinement and parameter adjustments, it was possible to obtain numerical results similar to those observed experimentally, thus enabling the numerical simulation of foundation behavior.

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## Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

## Authors' contributions

Bárbara Estéfany Pereira: conceptualization, formal analysis, methodology, writing – original draft. Eduardo Augusto dos Santos Oliveira: validation, methodology. Jean Rodrigo Garcia: funding acquisition, investigation, methodology, project administration, resources, software, writing – review & editing.

## Data availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

## Declaration of use of generative artificial intelligence

This work was not prepared with the assistance of Generative Artificial Intelligence (GenAI).

## List of symbols and abbreviations

| | |
|---|---|
| $c$ | Cohesion |
| $c_{res}$ | Residual Cohesion |
| $d$ | Diameter of shallow foundations tested by various authors |
| $s_{adm}$ | Allowable displacement |

| | |
|---|---|
| $w$ | In-situ moisture content |
| ABNT | Associação Brasileira de Normas Técnicas |
| CAPES | Coordination for the Improvement of Higher Education Personnel |
| CEMSF | Experimental Field Mechanics of Soils and Foundations |
| CNPq | National Council for Scientific and Technological Development |
| DPL | Light Dynamic Penetrometer |
| $E$ | Young's modulus |
| $E_{residual}$ | Residual Young's modulus |
| FAPEMIG | Minas Gerais Research Funding Foundation |
| $FS$ | Safety factor |
| MG | Minas Gerais |
| $N_{SPT}$ | Blow count for 30 cm penetration obtained from the Standard Penetration Test |
| $N_{SPT\ average}$ | Average of $N_{SPT}$ values |
| $N_{10}$ | Number average of blows for 10 cm penetration obtained from the Light Dynamic Penetrometer (DPL) test. |
| $N_{10\ average}$ | Average of $N_{10}$ values |
| QML | Quick Maintained Load |
| SML | Slow Maintained Load |
| SPT | Standard Penetration Tests |
| UFU | Universidade Federal de Uberlândia |
| $\phi$ | Friction Angle |
| $\varnothing$ | Piles diameters |
| $\varnothing_r$ | Raft diameter |
| $\gamma_{nat}$ | Unit weight |
| $v$ | Poisson's ratio |
| $\sigma_{10\,mm}$ | Stress corresponding to 10 mm displacement |
| $\sigma_{25\,mm}$ | Stress corresponding to 25 mm displacement |
| $\sigma_{adm}$ | Allowable bearing pressure |
| $\sigma_{inund}$ | Allowable bearing stress under flooded soil conditions |
| $\sigma_{máx}$ | Maximum applied pressure |
| $\sigma_{nat}$ | Allowable bearing stress under in-situ moisture conditions |
| $\sigma_{rup}$ | Ultimate bearing capacity |
| $\sigma_{\downarrow}$ | Percentage reduction in the ultimate bearing stress of foundations tested under flooded conditions, with and without preloading |

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