Computational analysis of the mechanical behavior of soil-cement mixtures applied to shallow foundation of small building

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Abstract. This paper aims to analyze computationally the mechanical properties of soil-cement mixtures applied to shallow foundations modeled from the project of a small building of social interest. The paper followed a methodology divided into three steps: systematic review, computational modeling and the result analysis of soil-cement mixture application in shallow foundations. Firstly, values for the mechanical properties of soil and soil-cement mixture were collected and estimated by equations from the literature. The properties were collected considering the same soil type for both soil and soil-cement mixture. Based on the collected data, it was possible to create a finite element computational model that allowed to perform the stress analysis. The dimensions and the loads applied to the model were estimated from the standard project of building of social interest. The feasibility analysis of the mechanical properties of soil-cement shallow foundation were made on the graphs and figures generated from the computational modeling. The results allowed to evaluate the stress concentrations of the model and compare it to the strength of the soil-cement mixture. Finally, this investigation plays a fundamental role in the production of knowledge about the mechanical behavior of soil-cement mixtures applied to shallow foundations of small buildings.

Keywords: soil-cement, shallow foundation, computational modeling.

1 Introduction

Civil construction industry has increasingly sought to improve materials and technologies that aim to optimizing and simplify the construction process. In this way, shallow foundations built from soil-cement mixtures have been used in small buildings of popular interest as an economical and viable alternative.

According Duan and Zhang [1], soil-cement has been widely used in soft soil foundation reinforcement, slope support, and channel lining in construction projects, such as roads, bridges and ports. In Brazil, the production and application of soil-cement are more expressive in paving projects, where approximately 90% of the country's highway bases are made of compacted soil-cement, and, in less proportion, for soil improvements on small building foundations, dams and containments [2].

Soil-cement mixtures have the advantages of easy access to draw materials, low price, and convenient construction [1]. However, there are several disadvantages regarding the application of soil-cement. The main disadvantage is due to the numerous types of existing soils, since these are directly related to the physical and mechanical characteristics of the soil-cement mixture [3]. In addition, soil-cement mixtures tend to have lower values for the mechanical properties, as unconfined compressive strength and shear strength for example, and greater deformation in engineering projects [1].

Although several authors have published papers about the characteristics of soil-cement, there are still few studies dealing with this material applied to shallow foundations. It is worth to mention as examples of studies, Pinto [4] that proposed methods for the experimental characterization of soil-cement mixtures, Wang et al. [5] that stablished an interpretation of soil-cement properties and its application in numerical analysis, and Fan et al. [6]

that performed a review about the mechanical properties of soil-cement mixtures. Therefore, knowing the particularity of the application in shallow foundation, it is evidenced the need of performing studies that corroborate for a better understanding for this subject.

In this context, this paper aims to analyze computationally the mechanical properties of soil-cement mixtures applied to shallow foundations modeled from the project of a small building of social interest.

2 Soil-cement mixtures

According to *Associação Brasileira de Cimento Portland* (Brazilian Association of Portland Cement) - ABCP [7], soil-cement is the material resulting from the homogeneous, compacted and cured mixture of soil, cement and water in adequate proportions. Basicly, any type of soil can be used to produce the mixtures. However, the most suitable soils are those with a sand content between 45% and 50%. Another important fact is that the soil to be used in the mixture can be extracted from the construction site itself. Furthermore, the resulting product from soil-cement mixtures with an optimal degree of compaction, is a material with good compressive strength, impermeability index, durability and low volumetric shrinkage index [7].

Since the 1950, researches have carried out experimental tests for the strength properties of soil-cement mixtures and have tried to relate them to each other [3]. The simple compressive strength, or unconfined compressive strength, is the most usual property found on the studies. For this reason, Fan et al. [3] mentioned studies that established relationship between unconfined compressive strength and other properties of soil-cement mixtures, such as Young's modulus (E), cohesion (c) and internal friction angle (ϕ).

For a basic computational analysis of the mechanical behavior the usual properties requested are Young's modulus (E) and Poisson's ratio (v), which have a significant influence on the displacement. Those elastic properties are not easily determined for soil-cement mixtures due to the innumerous variables that can influence on the resulting values. For example, Balmer [8] found that the Young's modulus of soil-cement mixture increases with cement dosage and varies from 0.69 GPa to 5.24 GPa.

Therefore, the development of a computational analysis strongly based on literature data can be considered a great ally in the feasibility verification of applying the soil-cement mixture, as it can serve as a preliminary and guiding study.

3 Methodological procedures

The study has been divided in three steps: systematic review, computational modeling and result analysis. It's worth mentioning that, initially, this study aimed to characterize experimentally the soil and the soil-cement mixture in order to collect physical parameters and resistance data. However, due to the actual Covid-19 pandemic situation, these data were collected from the literature in the systematic review step. All procedures are detailed described in the following subsections.

3.1 Systematic review

At first, the study aimed to seek previous work in the literature in order to collect soil classification and characterization corresponding parameters, as well as studies that presented physical and mechanical data of soil-cement mixtures. According to Pinto [4], soil-cement mixtures composed of fine-grained soil presents characteristic compressive strength values between 2.01 MPa and 3.15 MPa for mixtures made, respectively, with 3% and 6% of cement. Furthermore, it was possible to estimate the value of the Young's modulus of the mixture through the following formulation developed by Wang *et al*. [5]:

$$E = 30000\sqrt{q_u} \tag{1}$$

Where q_u represents the unconfined compressive resistance of the soil-cement mixture and the Young's modulus E is in kPa. For the mixture with 3% of cement it was obtained a value of E = 1,350 GPa, while for the mixture of 6% of cement it was obtained a value of E = 1,684 GPa. Poulous and Davis [9] stablished a formulation that was used to determine the Poisson's ratio, as it follows:

$$v = \frac{K_0}{K_0 + 1} \tag{2}$$

Where K_0 represents the pressure coefficient of the soil and can be determined through a relation developed by Jaky [10] and Michaloswki [11], that states the following:

$$K_0 = 1 - \sin\phi \tag{3}$$

Where ϕ corresponds to the friction angle of the soil. According to Wang et al. [5], the friction angle ϕ= 36° for fined-grained soils. Therefore, the Poisson's ratio value v = 0.29.

3.2 Computational modeling

In this step, it was developed a computational model in order to analyze the behavior of the structural elements composed of the soil-cement mixtures. The model was developed using a student version of the commercial software *Abaqus*. Once this study aimed to analyze the physical and mechanical behavior of the soil-cement mixture elements under uniform distributed loads, the boundary conditions were defined restricting only the vertical displacement.

The structural elements were designed from a small building project, outlining the construction and setting up beams with cross sectional dimensions equal to 35x35 cm and lengths varying from 3.0 to 7.15 meters (see Figure 1). In addition, the loads under which the elements were submitted were estimated through the Brazilian Standard ABNT NBR 6120 [12] technical norm that indicates loads for building structures calculations.

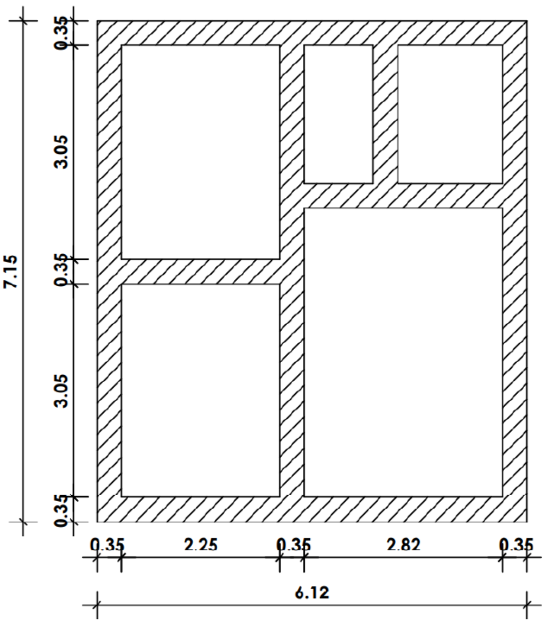

Figure 1. Structural elements and its dimensions

3.3 Result analysis

In this step, the computational model results were analyzed in order to observe the strains and acting stresses, and to compare them to the soil-cement mixture compressive strength. These acting stresses were classified as S11, S22 and S33, corresponding to the main stresses of the Cauchy stress tensor. Moreover, it is important to mention that S33 is the main interest of the study, since it acts perpendicularly to the structure surface, similarly as a real situation where the distributed loads acts in the vertical plane.

4 Results and Discussion

The results are divided in two sections: stress analysis and strain analysis. These results correspond to the closing investigation from the designed computational model. It is worth mentioning that for the analysis presented in the following subsections, it was used the soil-cement mixture with 3% of cement and mesh global sizes of GS = 0.100 and GS = 0.025 for both stress and strain analysis and also 6% of cement for the strain analysis comparison.

4.1 Stress analysis

In this analysis, it was observed that for the mesh of global size GS = 0.100 the magnitude of the acting compressive stress reached a maximum value of 26.77 kPa, while for the mesh of global size GS = 0.025 the maximum value was 42.70 kPa. Moreover, it is possible to notice that the difference between these values is given by the mesh refinement. It is important to mention that, according to the computational analysis results, the values of tensile and compressive strength of soil-cement mixtures found in literature are considerably higher than the stress that occur on the structural system. This indicates the feasibility of the application of soil-cement mixtures in shallow foundations, however further studies are necessary due to the large variety of soil. The results for the stress analysis are presented on Figure 2a and Figure 2b.

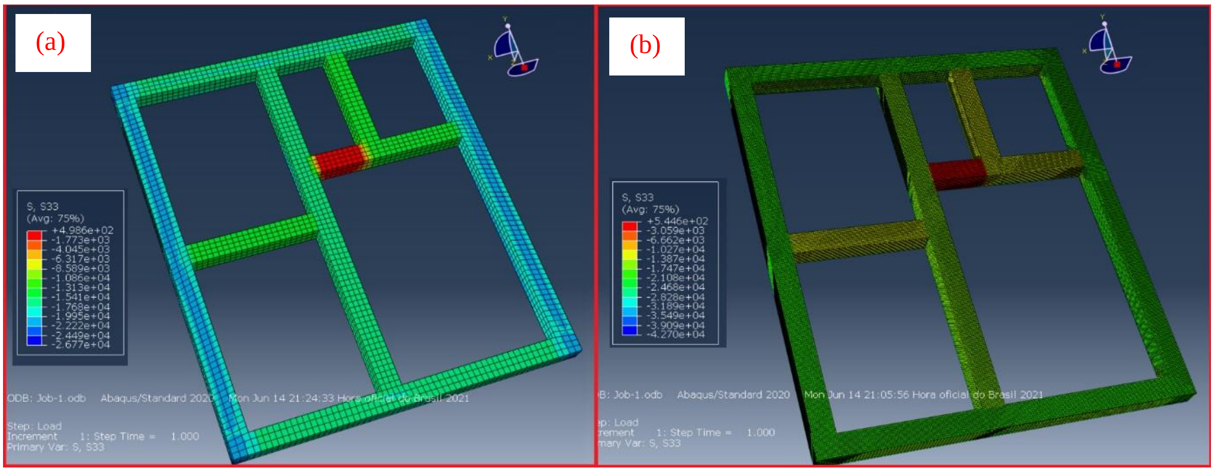

Figure 2. (a) Stress (S33) magnitude values for a mesh global size GS = 0.100 (b) Stress (S33) magnitude values for a mesh global size GS = 0.025

4.2 Strain analysis

In this analysis it was observed that for the mesh of global size GS = 0.100 and 3% of cement the magnitude of the deformation U reached a maximum value of $7.385{\cdot}10^{-3}$mm, while for the mesh of global size GS = 0.025 and 3% of cement the maximum value was $6.683{\cdot}10^{-3}$mm. Similarly, to the stress analysis, it was observed a slight difference between the values due to the mesh refinement. However, despite of that difference the magnitude of the deformation remained considerably small. The results for the strain analysis are presented on Figure 3a and Figure 3b.

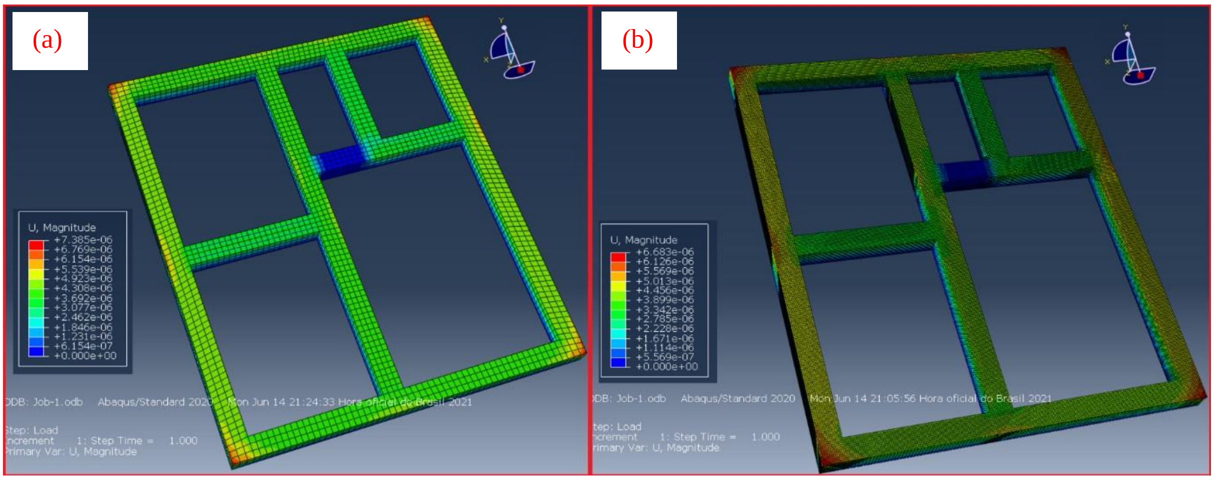

Figure 3. (a) Strain (U) magnitude values for a mesh global size GS = 0.100 and 3% of cement (b) Strain (U) magnitude values for a mesh global size GS = 0.025 and 3% of cement.

It was also analyzed the corresponding models of global sizes GS = 0.100 and GS = 0.025, both mixtures with 6% of cement. The model that corresponds to a global size GS = 0.100 reached a maximum deformation magnitude value of $5.920{\cdot}10^{-3}$mm, while for the mesh of global size GS = 0.025 the maximum value was $5.358{\cdot}10^{-3}$mm. Furthermore, the increment of cement in the mixture raised the respective Young's modulus, and as a result there was a slight reduction on the deformation magnitude values. The results for the strain analysis mentioned above are presented on Figure 4a and Figure 4b.

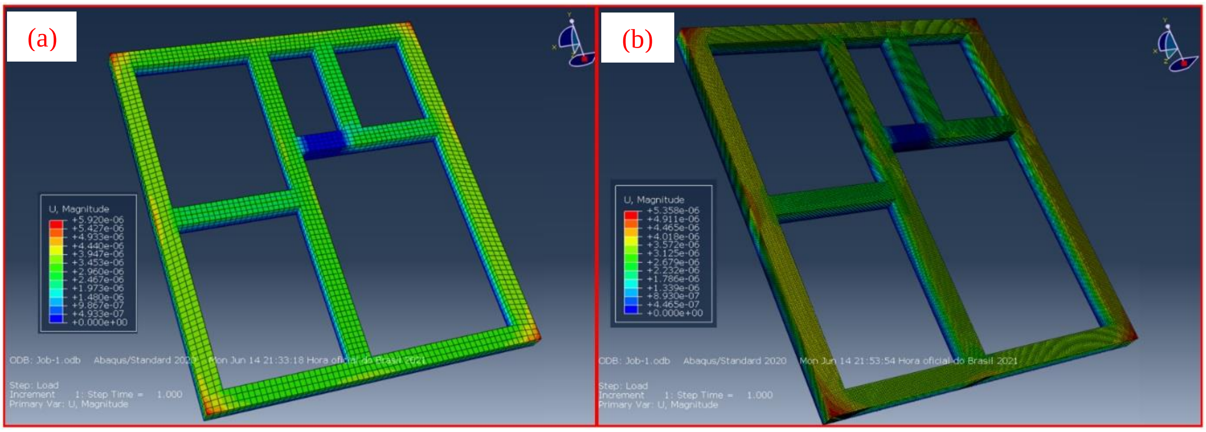

Figure 4. (a) Strain (U) magnitude values for a mesh global size GS = 0.100 and 6% of cement (b) Strain (U) magnitude values for a mesh global size GS = 0.025 and 6% of cement.

5 Conclusions

As a result of the performed analysis, it was possible to observe that the acting stress S33 reached a maximum magnitude value of 42.70 kPa, considerably smaller than the characteristic compressive strength of the soil-cement mixture for the corresponding dosage (3% of cement), that was 2.01 MPa. Furthermore, it was attended that the magnitude of the deformation U was considerably modest, reaching its maximum value at $7.385 \cdot 10^{-3}$mm. Therefore, both physical and mechanical analysis indicates the feasibility of the soil-cement application to shallow foundations of small buildings. Finally, this investigation plays a fundamental role in the production of knowledge about the mechanical behavior of soil-cement mixtures applied to shallow foundations of small buildings.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property of the authors, or has the permission of the owners to be included here.

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