Exploring Topology Optimization in Geotechnical Engineering

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Abstract. Despite recent advancements in utilizing topology optimization in geotechnical engineering design, practical applications primarily focus on simple foundation design. In the view of this, this study aims to explore the application of topology optimization methodology to various geotechnical design problems. The optimization takes place in a finite portion of the soil, modeled via Finite Element Method (FEM) which is coupled with the rest of the semi-infinite soil, modeled via Indirect Boundary Element Method (IBEM). The optimization is carried out considering a linear bi-material interpolation through the three field Floating Point Topology Optimization (FPTO) method. Numerical results for the optimized foundations of plates and bridges presented and discussed.

Keywords: topology optimization, soil-structure interaction, coupled methods, floating-point topology optimization

1 Introduction

The rapid development of topology optimization (TO) techniques in the recent years has established the increasing use of these collection of strategies to design structurally efficient and innovative applications in various engineering fields ([1–3]). Although the field of geotechnical design did not initially keep pace with these advancements, recent studies, such as [4–6] have demonstrated the applicability of optimization methods in the efficient structural design of soil-structure interaction (SSI) systems. However, current studies still have limited practical applications, primarily due to high computational costs associated with simulating soil mechanical behavior. In this context, the current work explores different applications of topology optimization in SSI problems. The recently developed three-field FPTO method (Huang and Li [7]) is employed in conjunction with a coupled IBEM-FEM SSI formulation to investigate stiffness optimization of structural foundations in different design scenarios.

2 IBEM-FEM coupled formulation

The soil-structure interaction model considered in this work consists of a two-dimensional linear elastic structure half-buried in a two-dimensional semi-infinite soil layer resting on a rigid base. A finite portion of the soil alongside with the half-embedded structure is modelled by a finite element discretization, while the rest of the soil is modeled by a boundary element discretization formulated in terms of superposition of non-singular Green's functions for loads applied inside the soil layer. For details on this formulation, readers are referred to Siqueira et al. [8]. The final equilibrium equation for the SSI system is obtained by imposing continuity and equilibrium on the interface between the adjacent IBEM-FEM meshes:

$$\begin{bmatrix} \mathbf{K} & \mathbf{AT} \\ \mathbf{D} & -\mathbf{U} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{q} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f} \\ \mathbf{0} \end{Bmatrix}, \tag{1}$$

where the $\mathbf{u}$ is the vector of displacements of the finite portion of the system and $\mathbf{q}$ is the vector of fictitious loads representing the soil layer. $\mathbf{K}$ is the finite element stiffness matrix, $\mathbf{A}$ and $\mathbf{D}$ are coupling matrices, and $\mathbf{U}$ and $\mathbf{T}$ are influence matrices representing the soil elastic behavior.

3 Topology optimization

The aim of the present work is to obtain the stiffest configurations of structural foundations for a given volume of material. Consequently, the appropriate optimization problem associated is the classical compliance minimization with volume constraints, which has been extensively studied in the literature and basically consists of distributing structure material over the design domain in order to obtain the configuration with minimal elastic strain energy possible. The optimization algorithm selected for this task was the FPTO method. Initially proposed by Huang [9], this method is based on a floating projection technique to implicitly simulate the design variables 0/1 constraints, unlike the classical SIMP method ([10]) that employs a material penalization scheme to obtain a 0/1 solution. This approach results in the FPTO method being independent of material interpolation schemes, and with direct application to multiphysics systems. The optimization takes place in the finite element discretized design domain while an auxiliary post-processed smooth design is used as a stopping criteria (more details on Huang and Li [7]).

4 Numerical results

4.1 Plate example

In this section is presented the representative case of the optimization for a rigid plate foundation under a centered downward vertical load (Fig. 1). The foundation material is one hundred times stiffer than the soil and the prescribed final volume for the foundation is 5% of the design domain total volume. The radius of the smoothing filter considered is twice the size of an element.

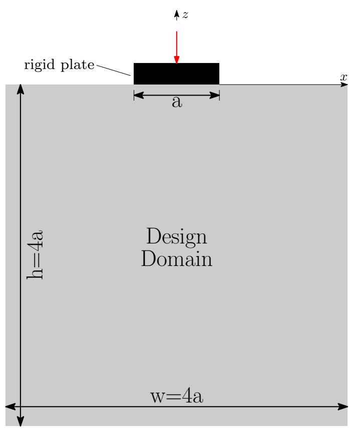

Figure 1. Plate foundation optimization problem.

Figure 2 presents both the element based and smooth design for the final optimized foundation design. The inclined pile design is consistent with previous results ([8]) obtained with BESO and SIMP, although the circular geometry at the bottom end of the pile has not been observed in previous results and must be investigated further. The difference in the final compliance between both designs is less then 2% and it was obtained in 245 iterations, indicating a smooth optimization convergence.

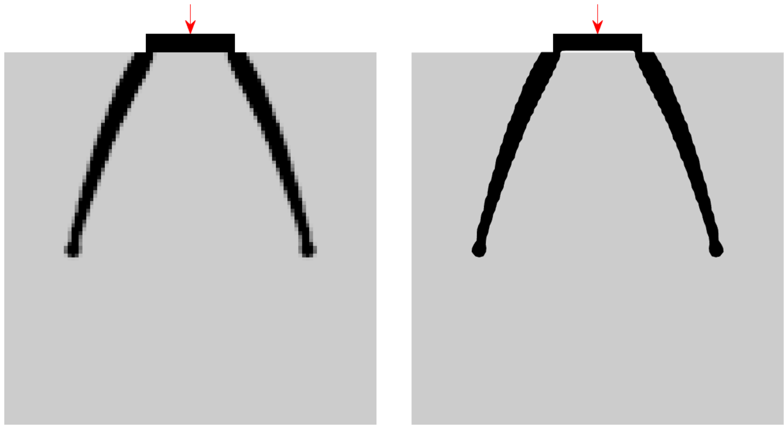

Figure 2. Final optimization solution for the plate foundation: element based design (left) and smooth design (right).

4.2 Bridge example

In this section the plate foundation problem is further investigated as a rigid bridge problem. A rectangular void region is considered under the plate in order to simulate a hole. The material for the foundation structure and soil are the same as previous section. The effect of the hole's depth on the final optimized solution is investigated. Figure 3 illustrate the effect of the depth of the hole on the optimization final solution for the same quantity of foundation material as the plate example. Note that the influence of the hole's depth is not clear and mostly not relevant to the optimized solution. Piles with rounded edges are also observed.

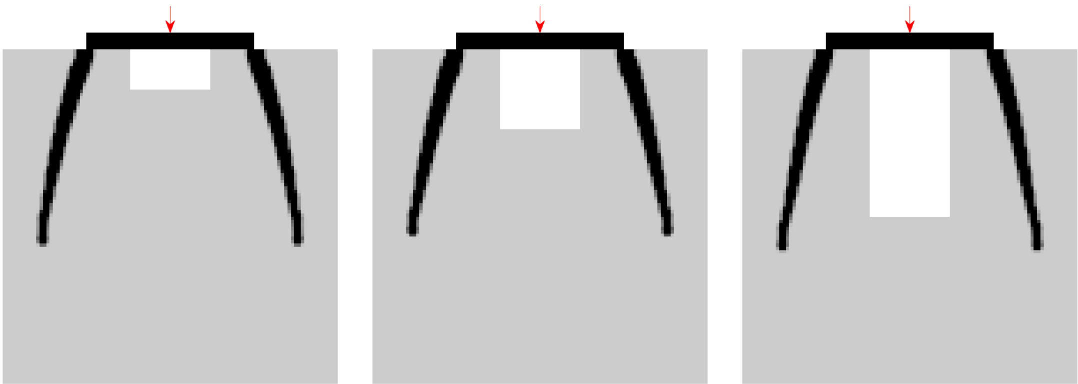

Figure 3. Effect of hole depth on the final optimization solution for the bridge problem (element based design): depth 0.05a (left), depth 1a (center) and depth 2a (right).

5 Final remarks

This work investigated the application of the topology optimization to geotechnical engineering problems. A coupled finite-boundary element formulation for the soil-structure numerical model in conjunction with the FPTO algorithm were considered in the analysis. Optimized results for the foundation of two dimensional plates and bridges were presented, showing that the has good applicability to soil-structure systems.

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