An insight into the sensitivity of seismic basin effects to boundary conditions

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Abstract

Under complex stratigraphic and morphological conditions, such as the ones typically occurring in basins, the realistic assessment of seismic site effects requires a refined, continuum-based modeling of the entire soil deposit. The effectiveness of the assessment is highly influenced by the assignment of boundary conditions. In this context, this paper presents the preliminary steps of a broader research path aimed at developing practice-oriented standards for basin effects under seismic loading. To this end, site response analyses are carried out on an example two-dimensional basin model using OpenSees and comparing the outputs of multiple boundary conditions techniques. Specifically, the following methods are employed along the lateral boundaries: kinematic constraints, Lysmer and Kuhlemeyer viscous absorbers, massive boundary columns and free-field boundary columns. The propagation of the seismic waves from the outcrop to the lower boundary is instead analyzed through a deconvolution procedure. Although preliminary, these results highlight some potentially relevant factors influencing the seismic performance of boundary conditions and suggest some practical indications about their applicability in boundary value problems.

Keywords: Basin effects, Site response analysis, Boundary conditions, Parametric study, OpenSees

1 Introduction

Site response analysis (SRA) is a fundamental approach for the assessment of the seismic behavior of the subsoil. Given the complexity of the phenomena involved in seismic wave propagation, SRA can entail advanced numerical modeling in lieu of simplified approaches like those typically included in technical provisions.

A critical aspect of advanced numerical modeling is the accurate definition of boundary conditions (BCs), which can influence significantly the reliability of the predictions as they define how the model interacts with the lateral and underlying subsoil not represented numerically. A less realistic definition of BCs can lead to under- or overestimating site effects, thereby hindering the quality of seismic hazard estimation at site-scale.

This paper illustrates the results of a study included within a broader research project aimed at developing seismic code-compatible approaches for quantifying basin effects [1, 2]. While previous studies focused on the influence of BCs on specific SRA-related problems (e, g., [3, 4]), the ongoing research effort will involve an extensive parametric analysis and the subsequent systematic, data-driven assessment of these effects. In this view, this paper provides an initial insight into the comparative assessment of BC modeling effects on SRA by analyzing a single basin model in a seismic scenario. SRA is conducted by using distinct BC techniques, and the resulting outcomes are critically compared and interpreted.

2 Numerical modeling

By virtue of its versatility and open-source policy, the Python version of the finite element analysis framework OpenSees [5] was used to implement a continuum-based numerical representation of the example basin, along with the definition of the seismic input, as detailed in the following sections [6].

2.1 Geometry

The reference geometry for the example numerical study is shown in Fig. 1. The basin is composed of a double layer of surficial deposits resting on a sigmoid-shaped bedrock. The geometry of the reference basin scheme is defined by the following dimensions (in meters): $H = 200m, H_1 = 100m, H_2 = 100m,\ L_i = 150m,\ L_{ol} = 200m,\ L_{or} = 300m,\ L_{el} = L_{ol}, L_{er} = L_{or}$, and $H_e = H$.

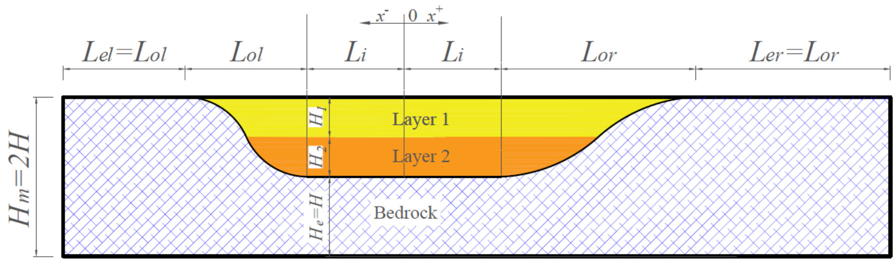

Fig. 1. Reference basin layout

2.2 Model

The cyclic behavior of the layers constituting the basin was described by the pressure-dependent multi-surface constitutive law (PDMY) developed by [7]. The PDMY provides a multi-linear response with kinematic hardening describing the nonlinear cyclic behavior of coarse-grained soils. The bedrock was instead modeled as a linear-elastic isotropic material (named EI hereinafter). The entire deposit is assumed to be dry.

The constitutive models were calibrated considering first the suggested values provided on the relative OpenSeesWiki webpage [8]. The subsequent assignment of material parameters was aimed at obtaining representative values of the stiffness moduli for different soil categories prescribed by European provisions (EC8, [9]). As per the latter, typical power laws were assumed for simulating the in-depth variation of the shear wave velocity.

2.3 Seismic input motion

Given the preliminary scope of this study, the seismic performance of the reference basin layout was investigated by considering a single seismic scenario. Specifically, the latter is represented by the horizontal EW component of 1980 Irpinia (Italy) earthquake recorded at the Bisaccia station. This time history is part of a suite of records selected for the broader purpose of the present research path, spanning over EC8-compatible target response spectra. Fig. 2 shows the acceleration time history, and the corresponding 5%-damped elastic acceleration response spectrum of the considered seismic motion.

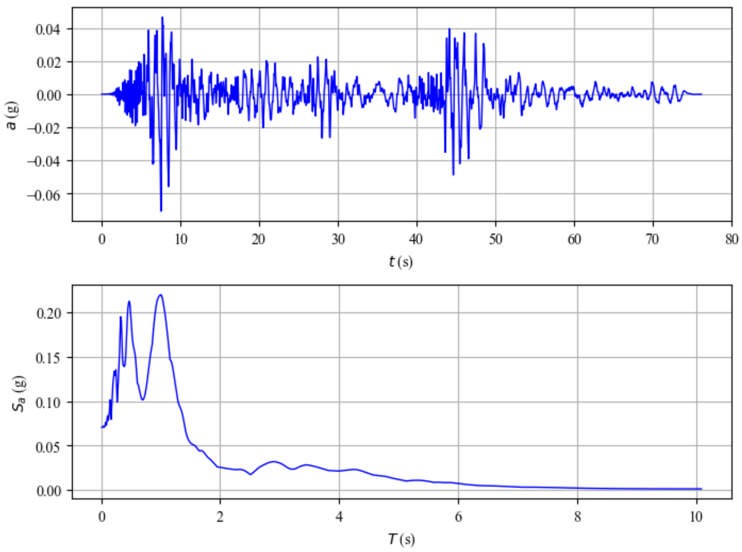

Fig. 2. Acceleration time history and response spectrum of the seismic input motion

2.4 Gravity analysis

The OpenSees numerical model of the reference layout (Fig. 1) was implemented according to a staged analysis procedure, aimed at reproducing the effective stress state of the soil under lithostatic conditions, as a fundamental point to get reasonable assessment of the dynamic performance. To this end, the adopted staged analysis simulated the progressive deposition of the superficial deposits composing the basin.

In the light of the above, gravity analysis was implemented as the succession of the stages shown in Fig. 3. Stage 1 was devoted to the initialization of the stress state in the bedrock only, restraining all nodes corresponding to basin layers. In Stage 2, the restraints to the nodes of Layer 2 in the basin (see Fig. 1) were removed and a new static analysis was carried out to let the system settle. Finally, Stage 3 reproduced the further modification of the stress state in the domain induced by the activation of the superficial basin layer, No. 1.

Boundary conditions

This study focuses on a comparative investigation on the seismic response of the considered case employing different modelling of lateral boundary conditions, namely:

I) EqualDOF: nodes along opposite boundaries at the same elevation undergo the same displacements [10].

II) L&K dashpots: viscous dampers are connected to the boundary nodes [11].

III) Massive columns: massive soil columns, having a thickness much greater than the soil elements along the boundary are introduced at both edges and rigidly connected to the inner domain in the horizontal direction (see, for instance, [12].

IV) Free-field columns: the edge columns in Point III are no longer directly connected to the nodes of the inner domain as viscous dashpots are interposed between them (e.g., see [12, 13]).

The corresponding layouts are shown schematically in Fig. 4. A displacement time history was imposed on the nodes at the base of the model, as the convoluted motion of the reference seismic record (Section 2.3).

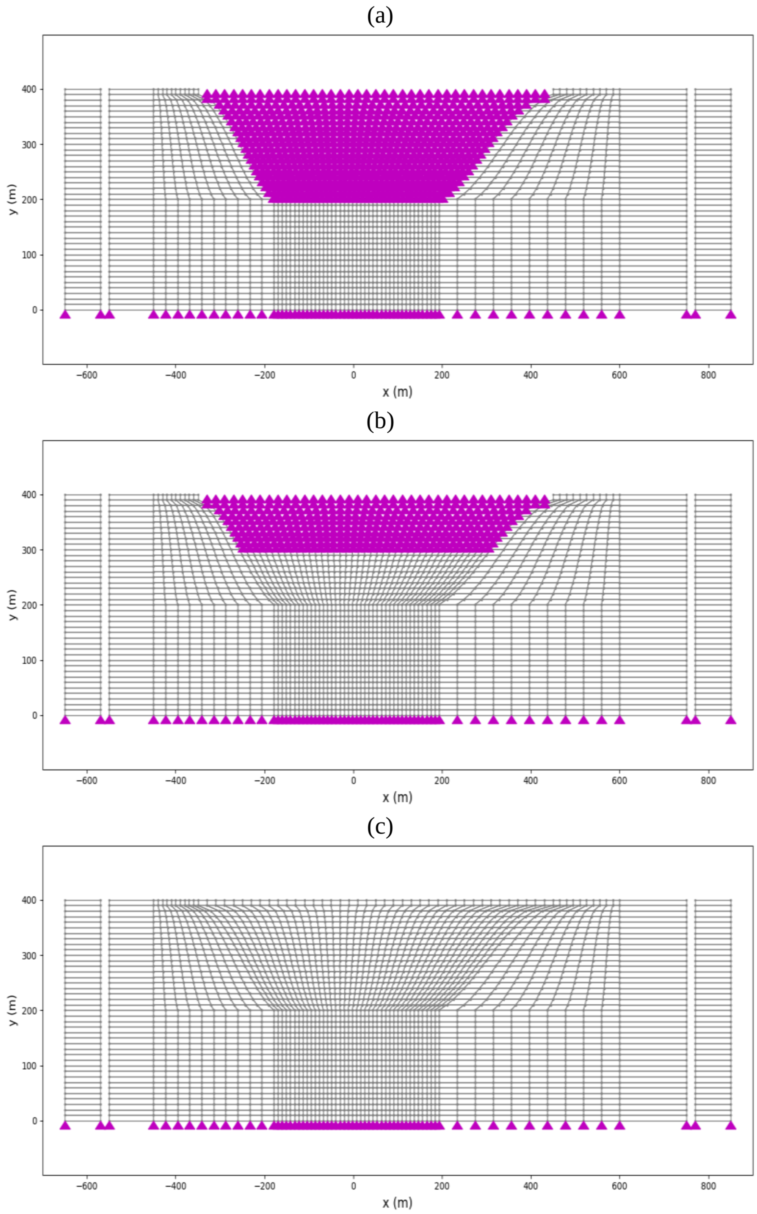

Fig. 3. Staged analysis procedure for gravity analysis: (a) realization of the bedrock domain; progressive introduction of the (b) first and (c) second superficial layers of the basin (restraints represented by pink triangles)

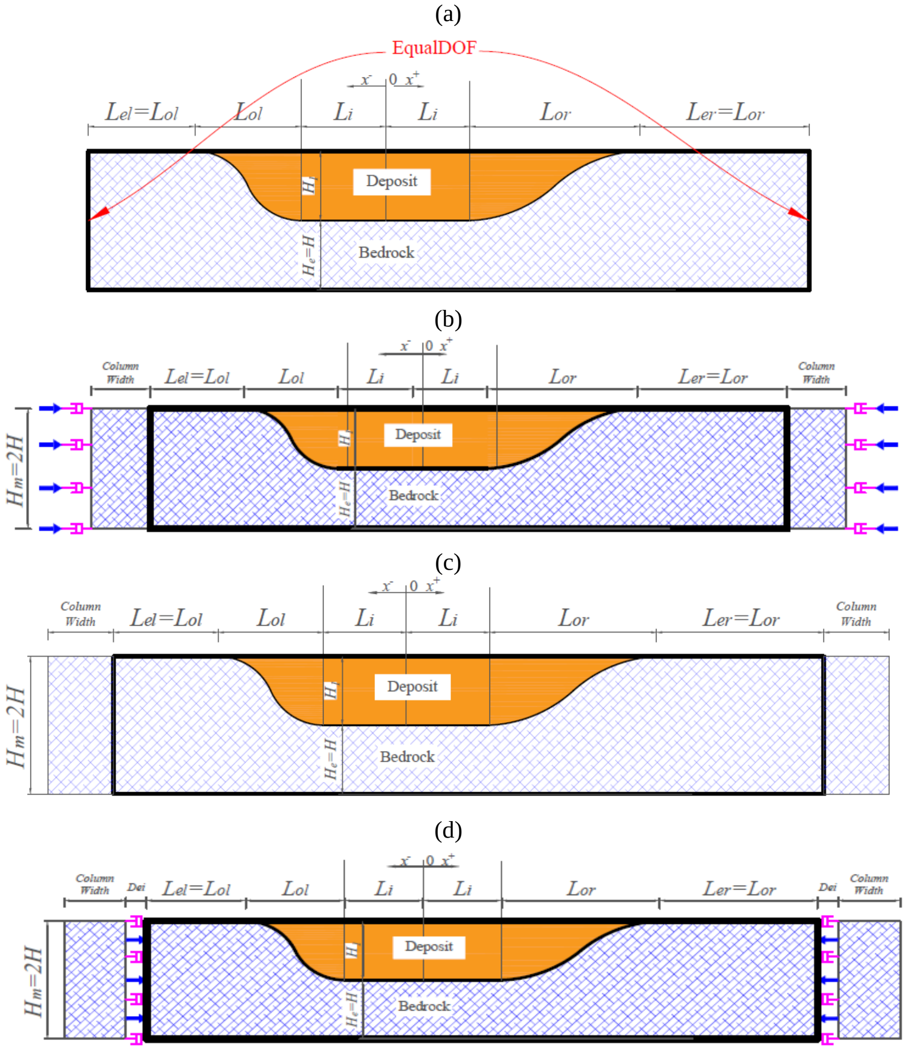

Fig. 4. Schematic representation of the considered techniques to model lateral boundary conditions: (a) kinematic constraints; (b) L&K dashpots; (c) massive columns; (d) free-field columns

3 Discussion of the results

The seismic performance of the basin was assessed in terms of horizontal displacements and spectral accelerations, the latter taken in correspondence to the fundamental period of the deposit ($T_1 = 4.82$ s) as a concise indicator of dynamic amplification effects typically of interest for assessments of the built environment. For the considered seismic scenario, these quantities were computed for a set of seven scrutiny nodes, shown in Fig. 5, spaced along the ground level to capture the spatial variability of site effects and the relative influence of the adopted BCs.

The ability of the considered BCs to simulate realistically the displacement demand at the ground level was quantified in terms of the following concise indicator:

$$\frac{d_{\max}(\text{ref})}{d_{\max}(\infty)} \tag{1}$$

where $d_{\max}(\text{ref})$, is the maximum horizontal displacement computed with the considered model (see Cases I-IV in Section 2.5) and $d_{\max}(\infty)$ is the one relating to an "enlarged model" of the basin, i.e., a model having a horizontal extension of the bedrock 10 times greater the one of the basin, making boundary effects in the latter negligible. The relative results are represented in Fig. 6.

Similarly, a spectral acceleration ratio was defined as:

$$\frac{S_{\text{a},\,\text{T}_1}(\text{ref})}{S_{\text{a},\,\text{T}_1}(\infty)} \tag{2}$$

with $S_{\text{a},\,\text{T}_1}(\text{ref})$ the reference spectral acceleration of the considered model and $S_{\text{a},\,\text{T}_1}(\infty)$ the one of the enlarged model. The results related to the analyzed cases are shown in Fig. 7

The results highlight the strong sensitivity of the basin response to the considered BCs methods. Notably, the use of L&K dashpots tends to underestimate the dynamic response because of the too much energy dissipated along the lateral boundary. Therefore, the use of this technique would imply a much greater horizontal extension of the model. By contrast, the use of EqualDOFs improves the basin response, with a slightly more pronounced amplification of the motion in proximity to the lateral boundaries due to the full reflection of the seismic energy reaching the boundary. Still, the free-field and massive columns provide a more consistent performance, more closely aligned to the one of the reference enlarged domain. A further element of interest lies in the asymmetry of the outputs, observed both in terms of displacement and spectral acceleration ratios, stemming from the non-symmetric geometry of the basin. Interestingly, displacement ratios are lower on the right side of the basin (where the

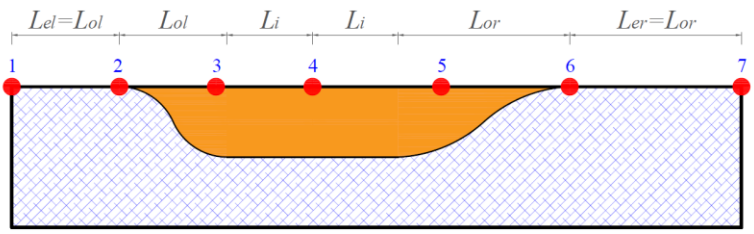

Fig. 5. Scrutiny nodes

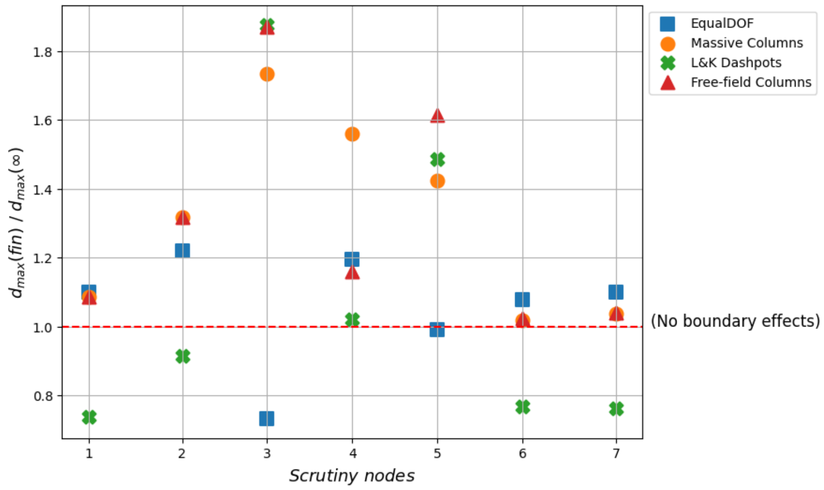

Fig. 6. Displacement ratio plotted as a function of the scrutiny nodes in the basin.

extent of the basin flank is larger) with respect to the left side, while spectral acceleration shows the opposite behavior. This is in agreement with the outcome of previous research (e.g., [1]), which highlighted the complex dependency of basin effects (both in terms of patterns and quantitative descriptive parameters) from numerous factors. Hence, the single modeling instance addressed in this paper only allows preliminary inferences regarding causal relationships.

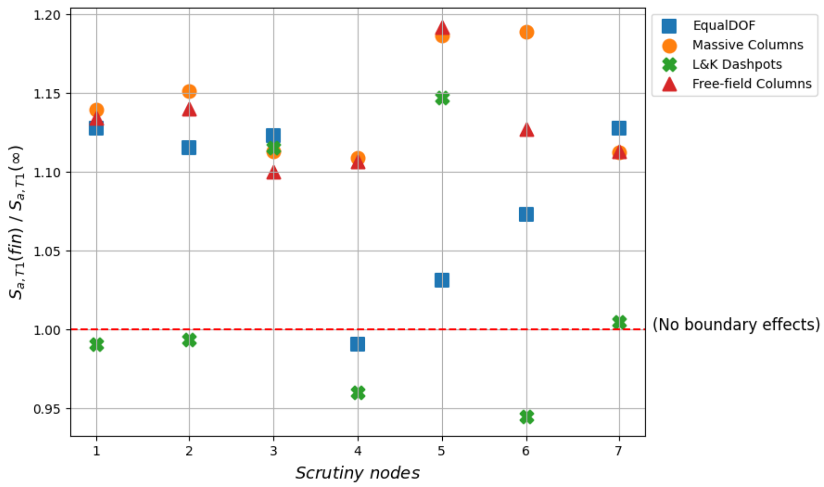

Fig. 7. Spectra acceleration ratio computed for the scrutiny nodes in the basin.

4 Concluding remarks

This paper presents preliminary results to be further developed and assessed in the context of a broader research project aimed at quantifying the impact of boundary conditions on basin seismic performance, particularly under complex topographic and stratigraphic conditions. The outputs of the considered modeling scenario highlight the sensitivity of basin performance metrics, such as displacement and significant spectral accelerations, to the choice of modeling strategies for boundary conditions. The comparison among different boundary conditions provides initial insights into the potential over- or underestimation of the response associated with each technique. The spatial variability of these effects is also highlighted, emphasizing the importance of a rational selection of boundary modeling techniques. In fact, this comparative study confirms the higher potential of free-field and massive columns to provide more reliable predictions of site effects under complex conditions, compared to L&K absorbers and kinematic constraints requiring a significant greater extension of the soil domain.

Acknowledgements

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