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Simplified approximate method for analysis of rocking systems accounting for soil inelasticity and foundation uplifting

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ABSTRACT

A simplified approximate method to analyze the rocking response of *SDOF* systems lying on compliant soil is introduced, accounting for soil inelasticity and foundation uplifting. The soil–foundation system is replaced by a *nonlinear rotational* spring, accompanied by a linear rotational dashpot, and linear horizontal and vertical springs and dashpots. Considering a square footing on clay under undrained conditions, the necessary moment–rotation (M–θ) relations are computed through *monotonic pushover* finite element (FE) analyses, employing a thoroughly-validated constitutive model. *Cyclic pushover* analyses are performed to compute the damping–rotation (C_R–θ) relations, necessary to calibrate the rotational dashpot, and the settlement–rotation (Δw–θ) relations, required to estimate the dynamic settlement. The effectiveness of the simplified method is verified through *dynamic* time history analyses, comparing its predictions with the results of 3D FE analyses. The simplified method is shown to capture the entire rotation time history $\theta(t)$ with adequate accuracy. The latter is used to compute the time history of dynamic settlement $w(t)$, employing a simplified approximate procedure. The proposed simplified method should, by no means, be considered a substitute for more sophisticated analysis methods. However, despite its limitations, it may be utilized for (at least preliminary) design purposes.

1. Introduction

Soil–foundation–structure interaction (SFSI) has been the object of extensive research over the last decades in an attempt to gain deeper insight into the seismic performance of structures (e.g., [35,59,36,21,57,61,22]). Nevertheless, a principal goal of foundation design, as entrenched in current seismic codes, is to maintain "elastic" soil–foundation response. According to capacity design principles, full mobilization of strength in the foundation is prevented, by guiding failure onto the superstructure (through application of appropriate over-strength factors). Strong earthquakes over the last 20 years, though, have shown that inelastic soil–foundation response may be inevitable. In fact, seismic records from the earthquakes of Northridge (1994) and Kobe (1995) have proved that very high levels of *PGA* and *PGV* can be experienced in near-fault zones. The recent Tohoku (2011) earthquake is another example of dramatically strong recorded *PGA* of up to 3 g [17].

Apparently, under such severe seismic shaking the assumption of elastic soil–foundation response cannot be considered realistic. Yet, it has been suggested by a growing body of researchers that soil–foundation nonlinear response may have a beneficial effect on the superstructure and it should be therefore considered in design (e.g., [50,24,53,18,46,54,32,19,3,2,27,28,38,39]). Nonlinear foundation behavior may involve *sliding* and/or *uplifting* of the foundation from the supporting soil, and/or mobilization of soil bearing capacity. In any of these cases, the finite capacity of the foundation may act as "rocking isolation" [46], limiting the inertia forces transmitted onto the superstructure, thus protecting it against seismic motions exceeding its design. Besides, such a design alternative offers greater safety margins in terms of ductility, since it exploits the inherent ductility associated with progressive soil failure.

To this end, an urgent need is arising to explicitly account for *nonlinear SFSI* and its beneficial effects in modern seismic design. Nonlinear foundation response could be allowed during strong seismic shaking, while ensuring that the developing displacements and rotations will not jeopardize the structural integrity of the superstructure. So far, a substantial amount of research has been conducted, including *experimental* (e.g. [45,18,41,37,9,51,19]) and *analytical* studies: (i) finite element (FE) or boundary element approaches, in which both the structure and the soil are modeled together in one single system through an assemblage of elements (e.g. [11,10,58,44,31,23,30]); (ii) rigorous plasticity-based macro-element formulations (e.g., [49,50,43,13,12,16]); (iii) Winkler-based

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approaches, where the soil is replaced by a series of distributed nonlinear springs and dashpots (e.g., [33,1,56]); and (iv) simplified approaches, such as the iterative procedure proposed by Paolucci et al. [52] to be incorporated to the Direct Displacement-Based Design (DDBD) method [55].

Nonlinear FE simulation, where both the superstructure and the soil–foundation system are modeled as a whole, is probably one of the best ways to simulate the response of rocking-isolated systems. However, such an approach is not computationally efficient and requires (reasonably) sophisticated and adequately validated constitutive models, rendering its application difficult in everyday engineering practice. Meanwhile, the current state-of-the art in nonlinear analysis of foundations emphasizes the development of macro-element models. According to this approach, the entire soil-foundation system is replaced by a single element, capable of portraying the rocking response in terms of rotation and dynamic settlement. However, the developed macro-element models have not yet been introduced in commercial FE codes and therefore, their use is limited. Moreover, extensive calibration is required in order to produce ready-to-use parameter "libraries" – a major issue that should be addressed in order to encourage their use in practice.

On the other hand, simplified methods that account for *nonlinear SFSI*, such as the procedure proposed by Paolucci et al. [52], may have substantial benefits, including: (i) easy implementation in commercial numerical analysis codes; (ii) limited calibration requirements; and (iii) applicability by non-specialists. Moreover, such simplified consideration of the nonlinear response of the soil-foundation system allows for more detailed and realistic modeling of the superstructure, which is likely to be a key issue in real-life engineering projects. Last but not least, by avoiding complicated 3D FE modeling, great savings in terms of computation time can be achieved. Consequently, the development of simplified approaches to account for *nonlinear SFSI* is of paramount importance in order to facilitate the application of such novel seismic design concepts in engineering practice.

Aiming to overcome the aforementioned barriers concerning the existing more sophisticated methods of analysis (such as macro-elements and 3D FE modeling), and to provide a framework for future research on the subject, this paper introduces a simplified approximate method to simulate the seismic response of a system rocking on compliant soil, accounting for fully inelastic soil response and geometric nonlinearities (such as foundation uplifting and second order effects). To demonstrate its effectiveness, the proposed simplified method is applied to a single degree of freedom (SDOF) system, representative of a bridge pier, comparing the predicted response with the results of more rigorous 3D FE analyses. The introduced simplified analysis method should, by no means, be viewed as capable of reproducing all aspects of complex soil response, or as a substitute of more elaborate methods. However, despite its limitations, it may be utilized for (at least preliminary) design purposes.

2. Problem definition and outline of the simplified method

As shown in Fig. 1a, the investigated problem refers to a SDOF system of height h carrying concentrated mass m, lying on a square surface foundation of width B on a clay stratum of depth z, undrained shear strength S_u, shear wave velocity V_s, and density ρ. To focus on the nonlinear response of the foundation, the oscillator is assumed practically rigid. Inspired by the simplified procedure proposed by Paolucci et al. [52], a simplified method is introduced to account for *nonlinear SFSI* effects. As illustrated in Fig. 1b, the soil-foundation system is replaced by springs and dashpots (in parallel). Since the considered problem is rocking-dominated, the horizontal (K_H and C_H) and vertical (K_V and C_V) springs and dashpots can be assumed elastic, and published solutions are directly applicable (e.g., [21]). As shown by Gajan and Kutter [20], the response is rocking-dominated when $h/B > 1$. In such a case, the cyclic rotation is much larger than the normalized cyclic sliding displacement, irrespective of the factor of safety F_S. Hence, the nonlinearities related to sliding can be ignored, which means that the related horizontal springs and dashpots can be reasonably approximated as elastic.

With respect to the rotational degree of freedom, instead of using an equivalent linear rotational spring, requiring an iterative procedure to capture the nonlinear response of the soil-foundation system (as in [52]), the proposed simplified method employs a *nonlinear rotational spring* accompanied by a *linear dashpot*, the properties of which are estimated through nonlinear 3D FE analyses. After the necessary calibration, the proposed procedure can be quite straightforward, not requiring iterations to compute

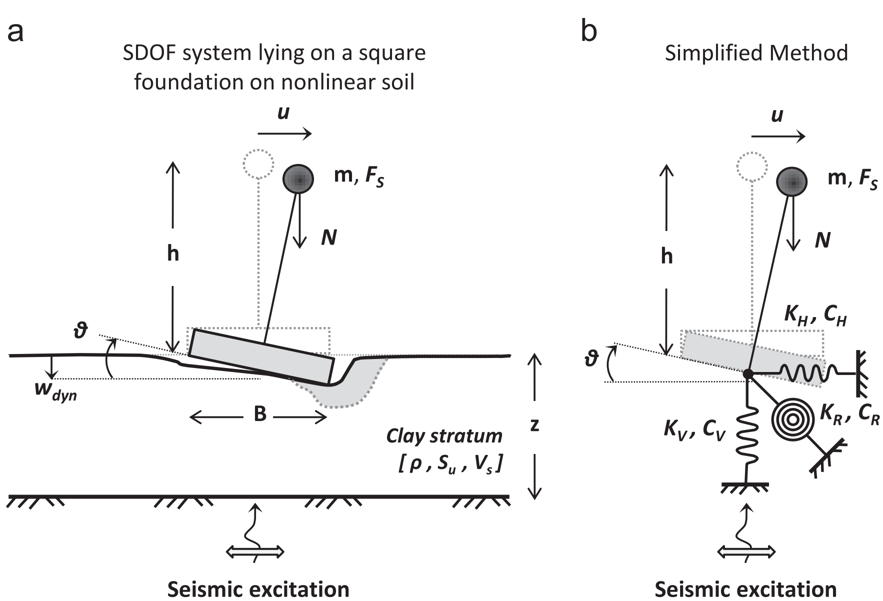

Fig. 1. Problem definition: (a) SDOF system lying on a square surface foundation on a homogeneous clay stratum; and (b) proposed simplified method where the soil–foundation system is replaced by a *nonlinear* rotational spring K_R, accompanied by a linear dashpot C_R, as well as linear vertical and horizontal springs and dashpots, K_V and C_V , and K_H and C_H, respectively.